The Far-Infrared Spectroscopy of the Troposphere Project – "FIRST"

Instrument Overview, Calibration, Recent Results
&
The Way Forward to "CLARREO"

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and

The FIRST Team

CLARREO Workshop
17 July 2007
College Park, Maryland

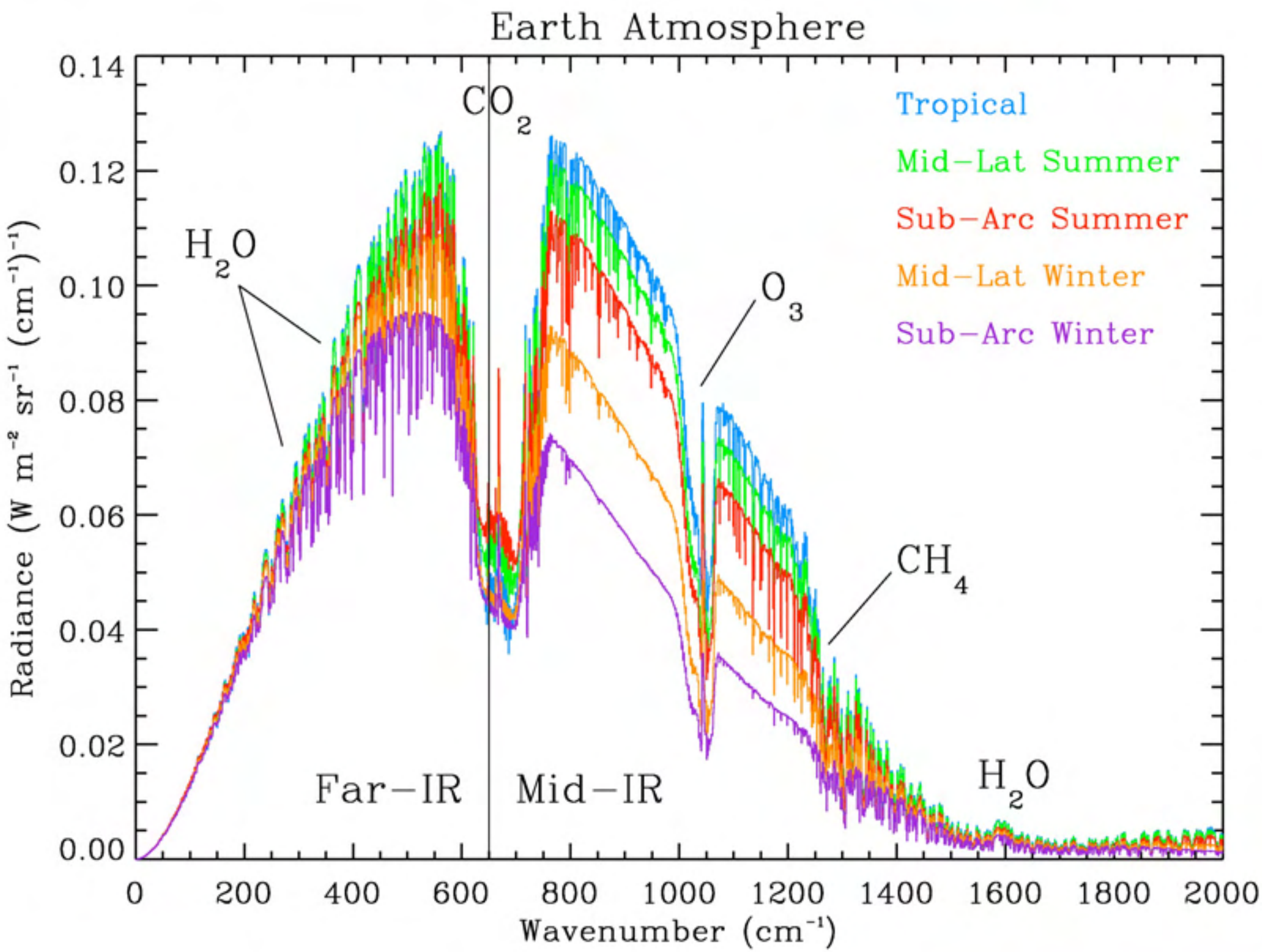
Partners

- We gratefully acknowledge our partners:
  - Space Dynamics Laboratory, Utah State University
  - Smithsonian Astrophysical Observatory
  - NASA ESTO
  - NASA JPL
  - NASA Balloon Program Office & CSBF
  - NASA Science Mission Directorate
  - NASA Langley SD and SED
  - The FIRST Science Advisory Team
  - TAFTS (UK) and REFIR (Italy) Far-IR Teams
  - AERI Team @ U. Wisconsin

Outline

- Science Justification
- Instrument Overview
- Calibration Overview
- Balloon flight nadir view results
- Ground-based zenith view results
- Way Forward to “CLARREO”

Outgoing Longwave Radiation



Compelling Science of the Far-IR

- Up to 50% of OLR (surface and atmosphere) is below 650 cm^{-1}.
- Up tp 75% of atmospheric OLR is beyond 650 cm^{-1}.
- Up to 50% of basic greenhouse effect is in far-IR.
- Clear-sky cooling of free troposphere occurs in far-IR.
- Upper tropospheric H_2O radiative feedback occurs in far-IR.
- Cirrus and LW cloud radiative forcing has major component in far-IR.
- Long-term climate “benchmark”.

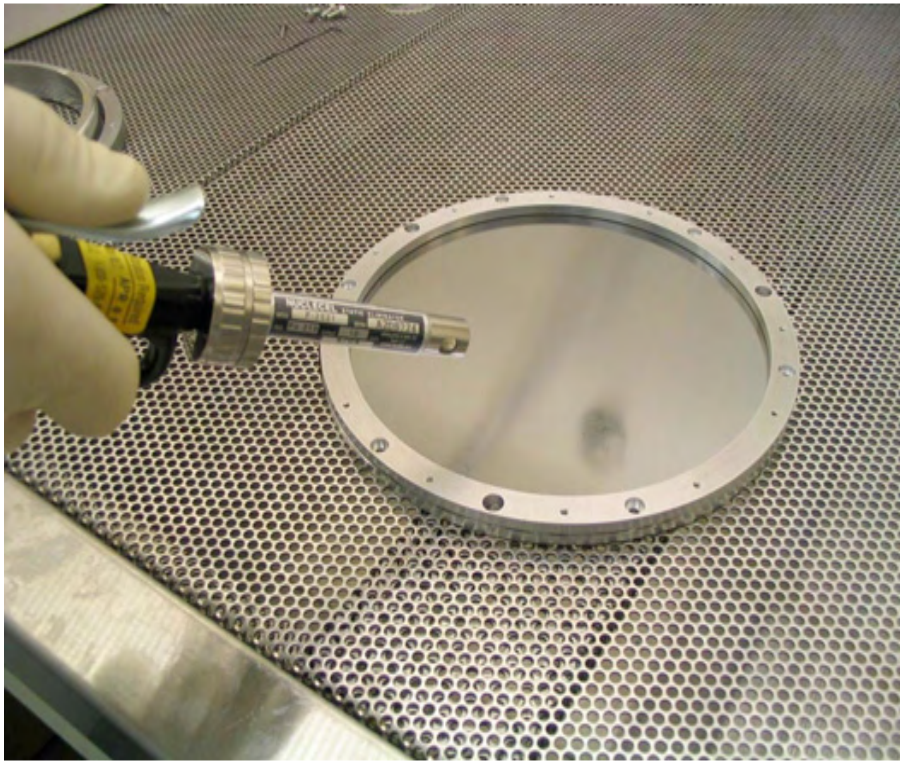
Making the Measurement: FIRST Project Goal

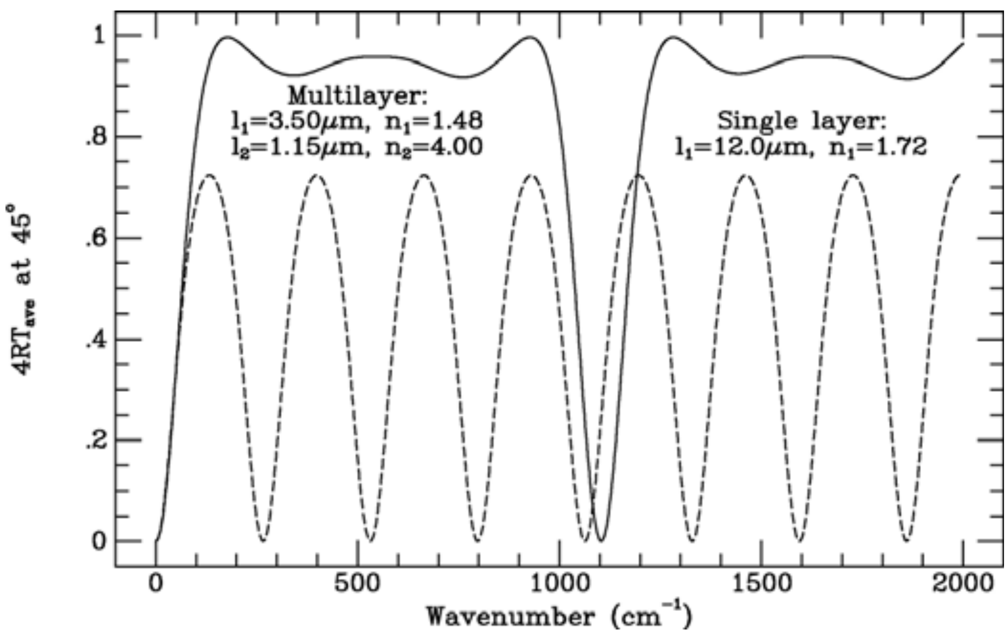
- Develop the technology required to measure the far-infrared spectrum from low-earth orbit with daily global coverage and 10 km IFOV:
  - Spectral coverage: 10 to 100 µm (1000 to 100 cm^{-1})
  - Spectral resolution: 0.625 cm^{-1} unapodized
    - 0.8 cm max OPD.
  - Scan time: 1.4s
  - NETD: 0.2 K (10 to 60 µm); 0.5K (60 to100 µm)
  - Optical throughput: sufficient to meet the NETD requirement for 100 fields in 1.4s (eg: 10x10 array)
- Demonstrate the technology in a space-like environment.

Required Technology Development

- Meeting FIRST measurement goals requires:
  - Broad band beamsplitter
    - Goal is >92% efficiency (4RT product) from 10-100 μm
  - Thermal noise limited uncooled detectors
    - This development was descoped in the first year and conventional liquid-helium cooled silicon bolometers were used.
  - High-throughput Fourier transform spectrometer
    - 0.47 cm^2 sr

Technology Development: Broadband Beamsplitter

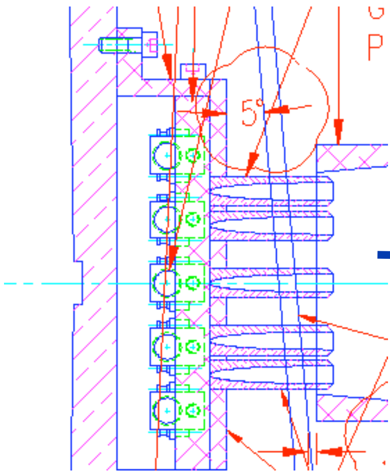


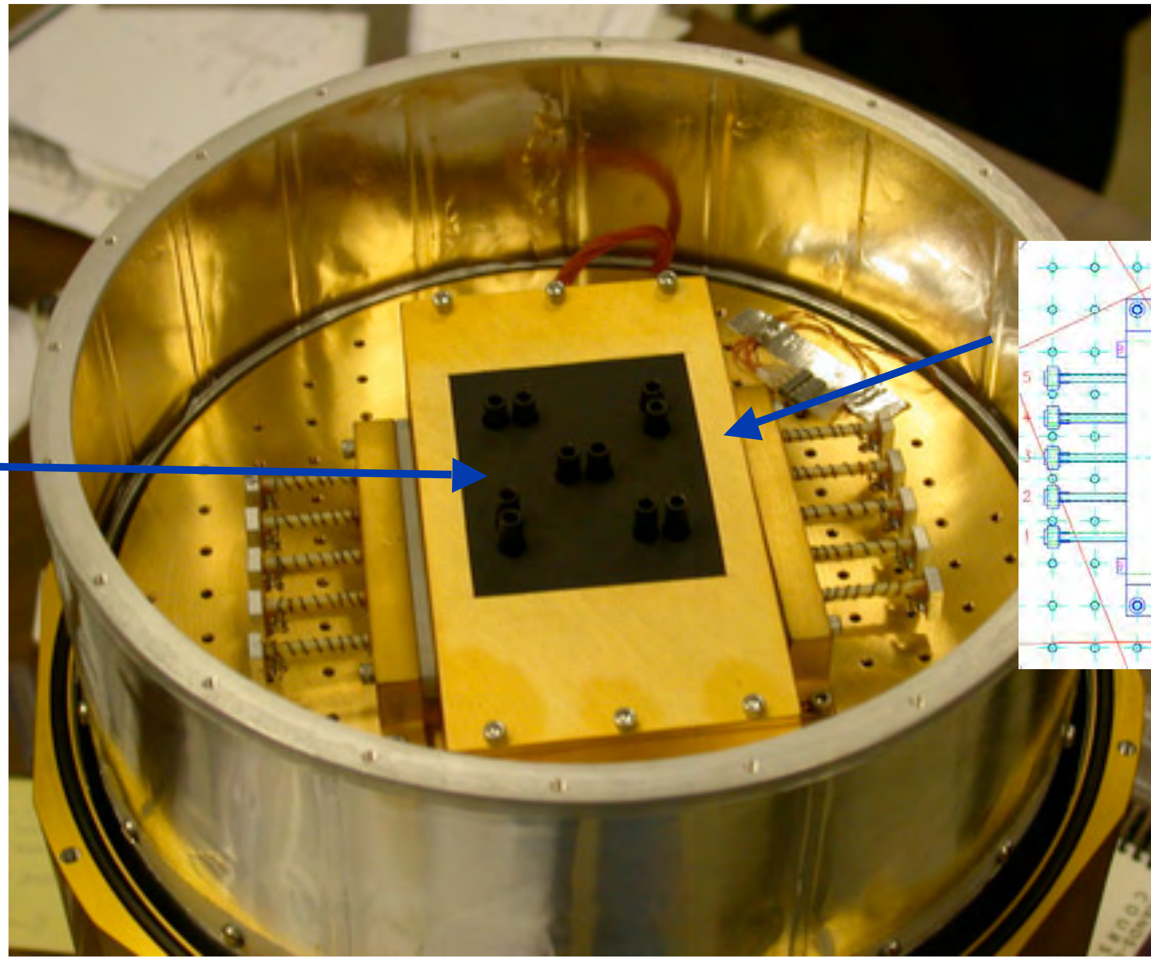


- Use Ge:Polypropylene bilayer pellicle beamsplitter

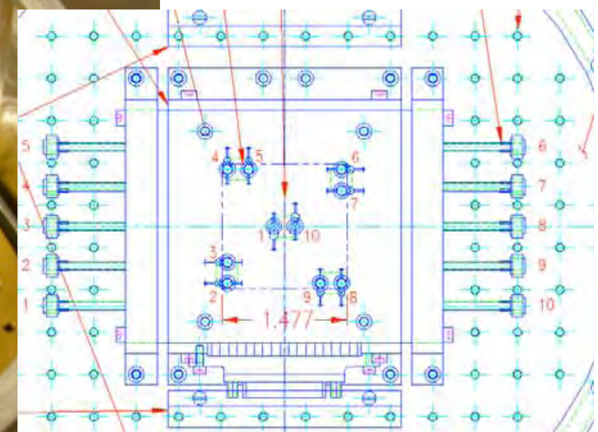
Technology Development: Broadband Focal Plane Array

Side view



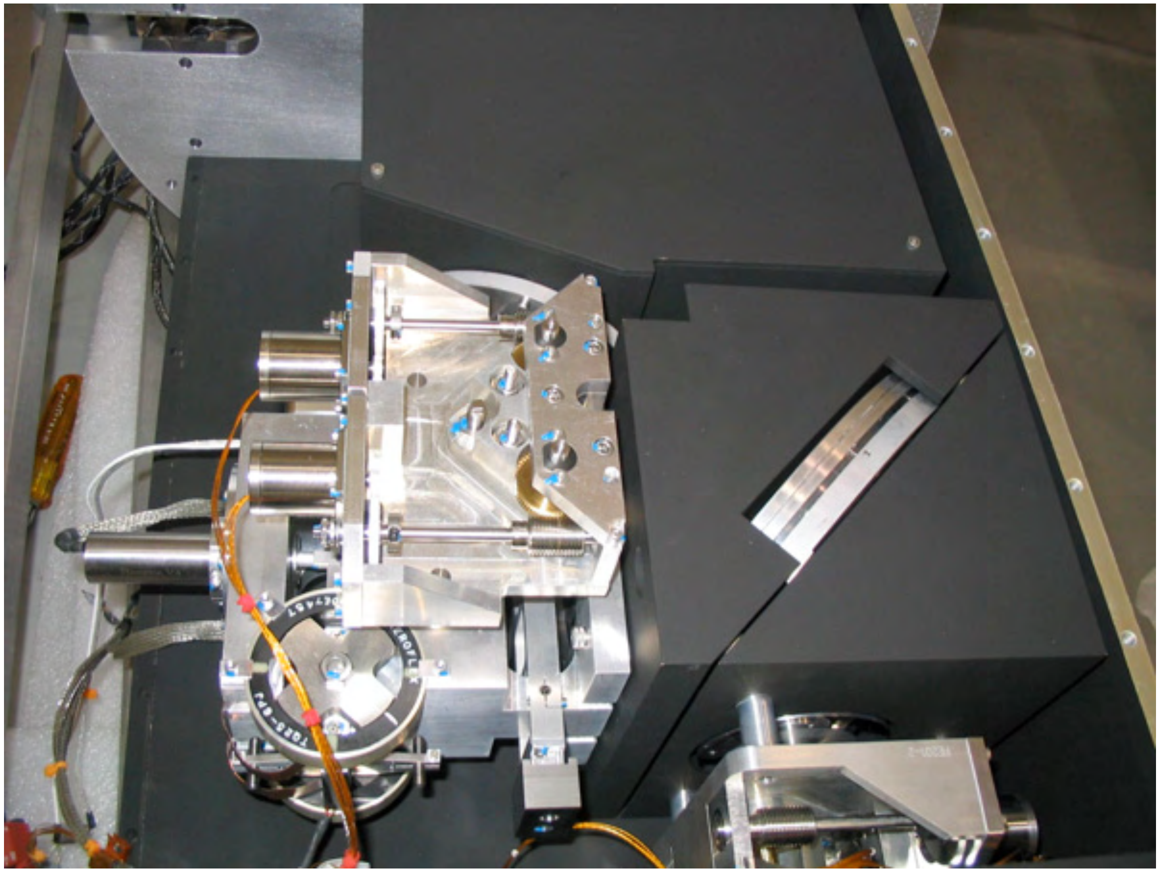


Top view



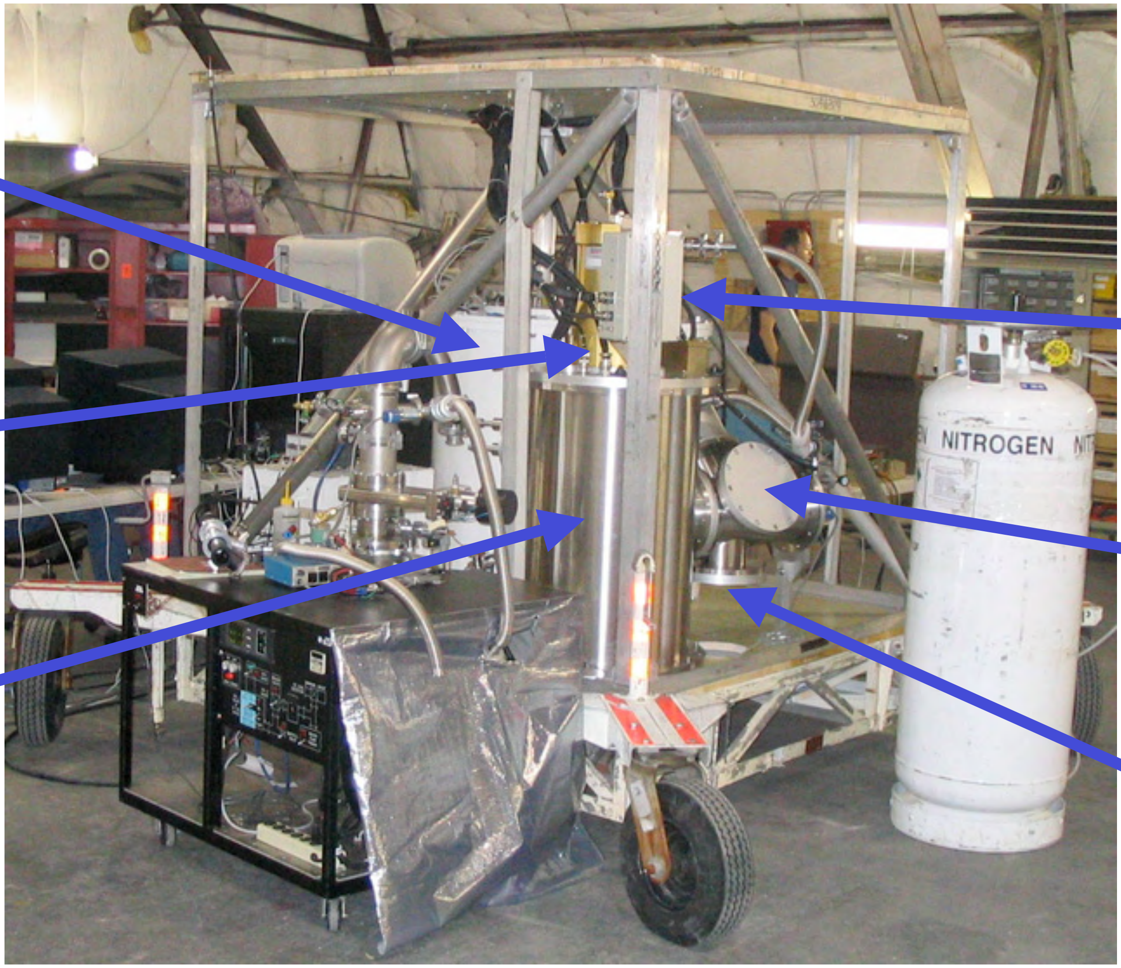
- Sparsely-populated array of discrete liquid-helium cooled silicon bolometers.

Technology Development: Fourier Transform Spectometer



- Flight-proven SDL Plane-mirror design maintains high performance and high throughput with compact design.

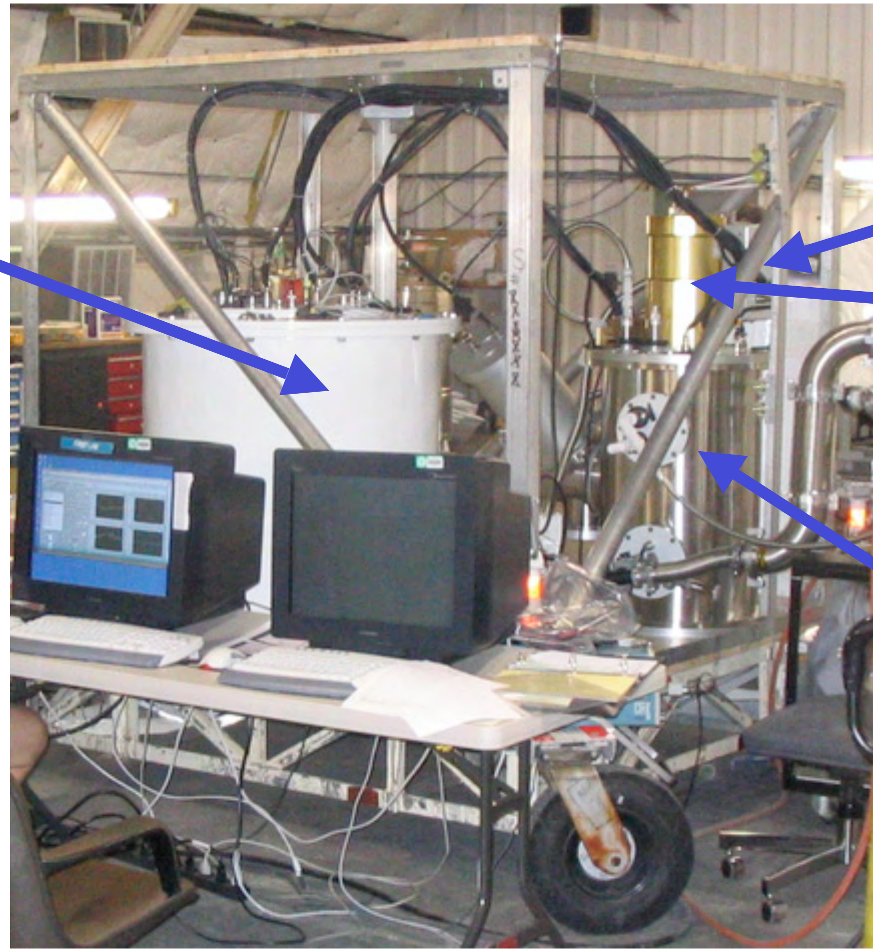
Instrument Overview: FIRST on Balloon Gondola



Front view

Instrument Overview: FIRST on Balloon Gondola

Electronics



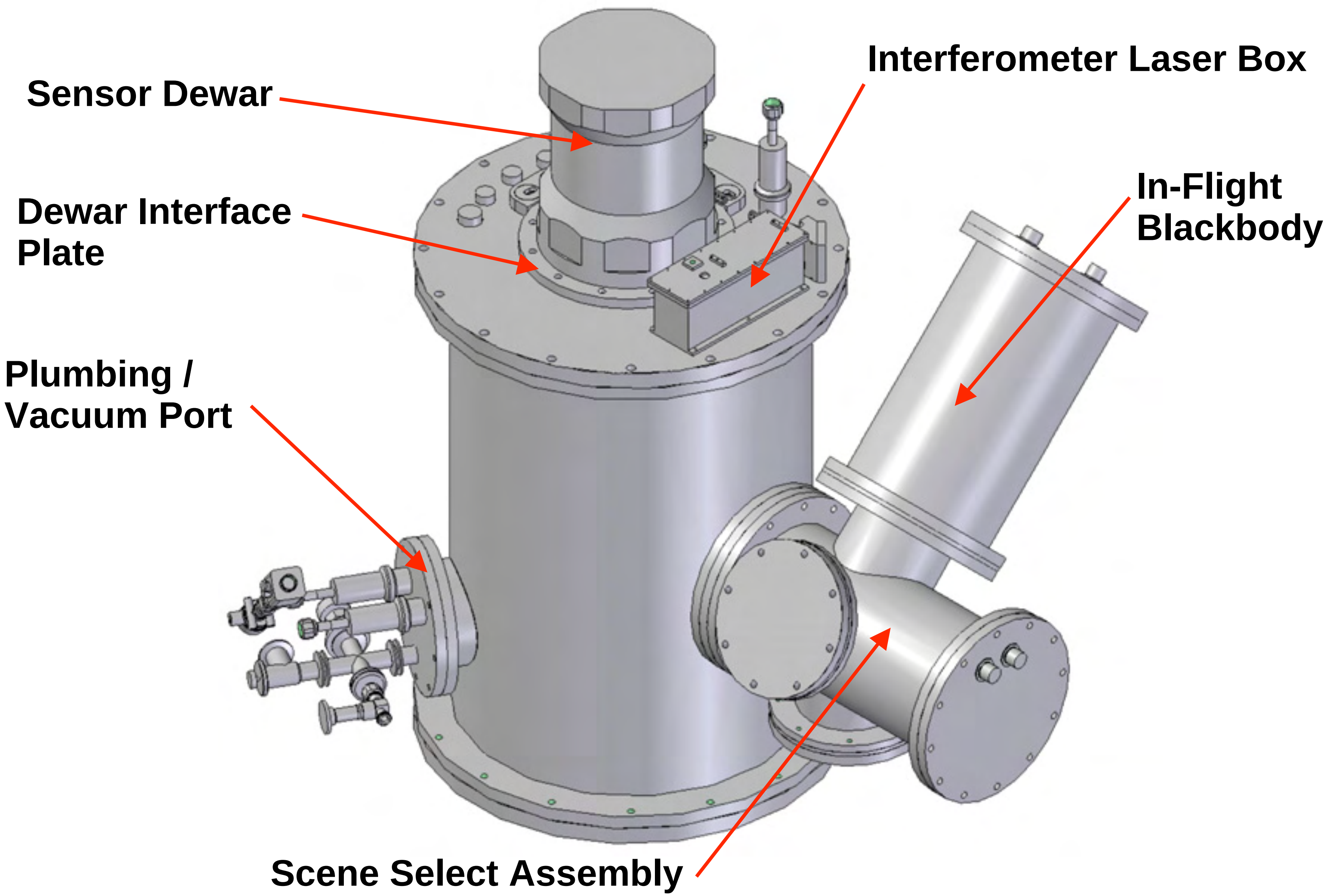
Detector preamplifier

Detector Dewar

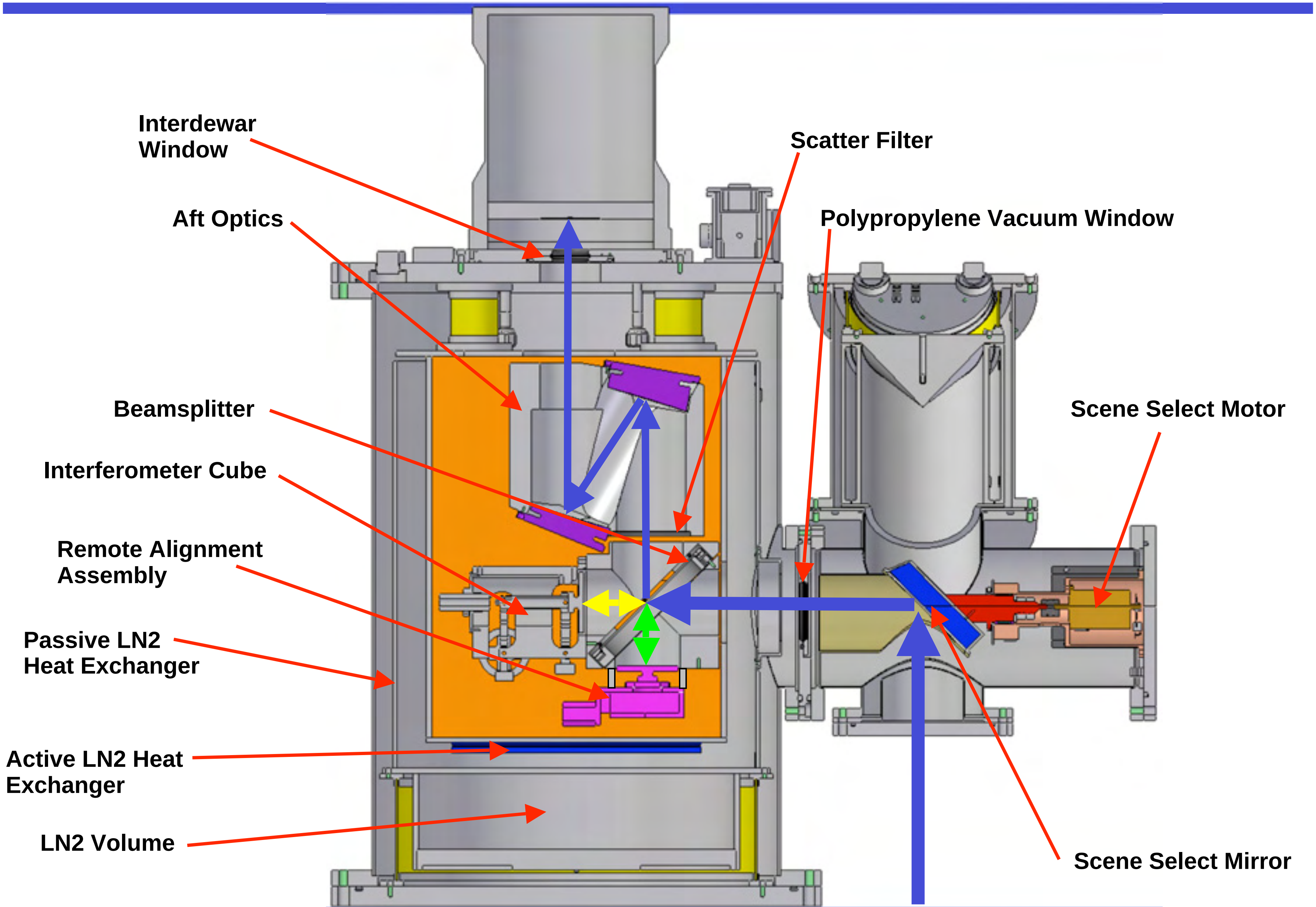
Spectrometer

Back view

FIRST Spectrometer Assembly



First Spectrometer Overview



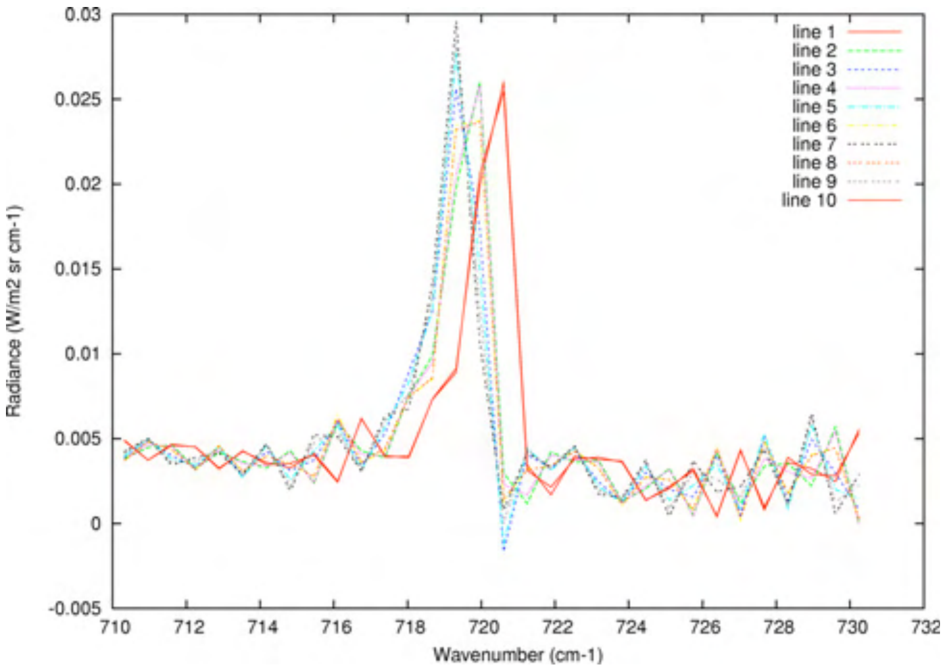
Calibration Overview

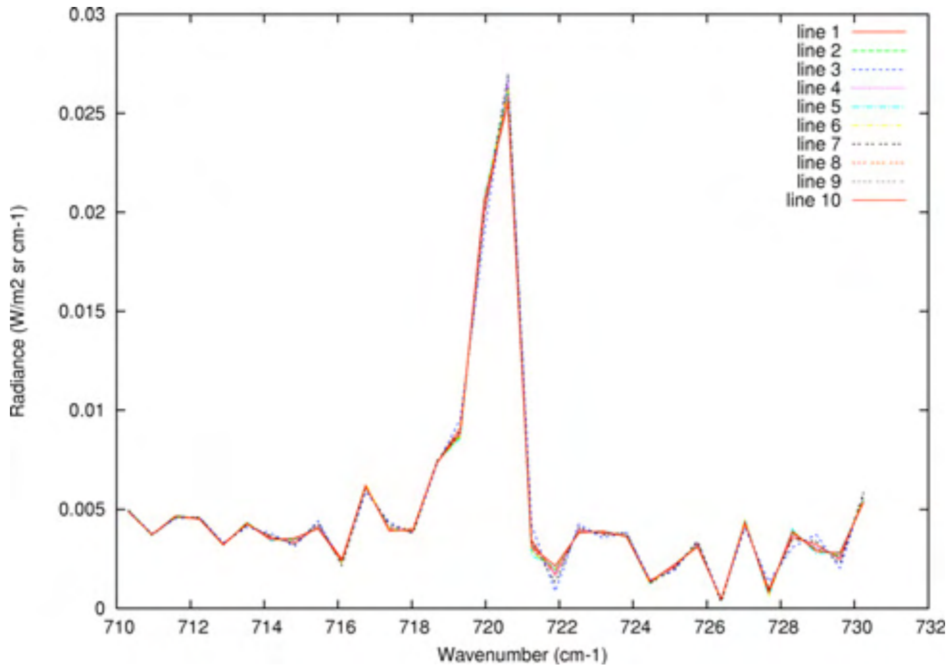
- Calibrate frequency scale
  - Correct for off-axis effects to put all detectors on same frequency scale
  - Determine global scale factor for comparison with model spectra
- Calibrate radiance scale
  - Use two blackbody method
  - Different configurations used for laboratory, balloon, and ground-based uplooking configurations.

Frequency Calibration

- Off-axis correction:
  - OPD (and spectral channel spacing) scales like cos(Θ), where Θ is the off-axis angle.
  - Our correction is to increase the length of the interferogram by 1/cos(Θ) before transforming, then truncate the spectrum to the standard length.
- Global Scale factor:
  - Derive from comparison between observed and model spectra for a few well-known isolated spectral lines.

Off-Axis Correction





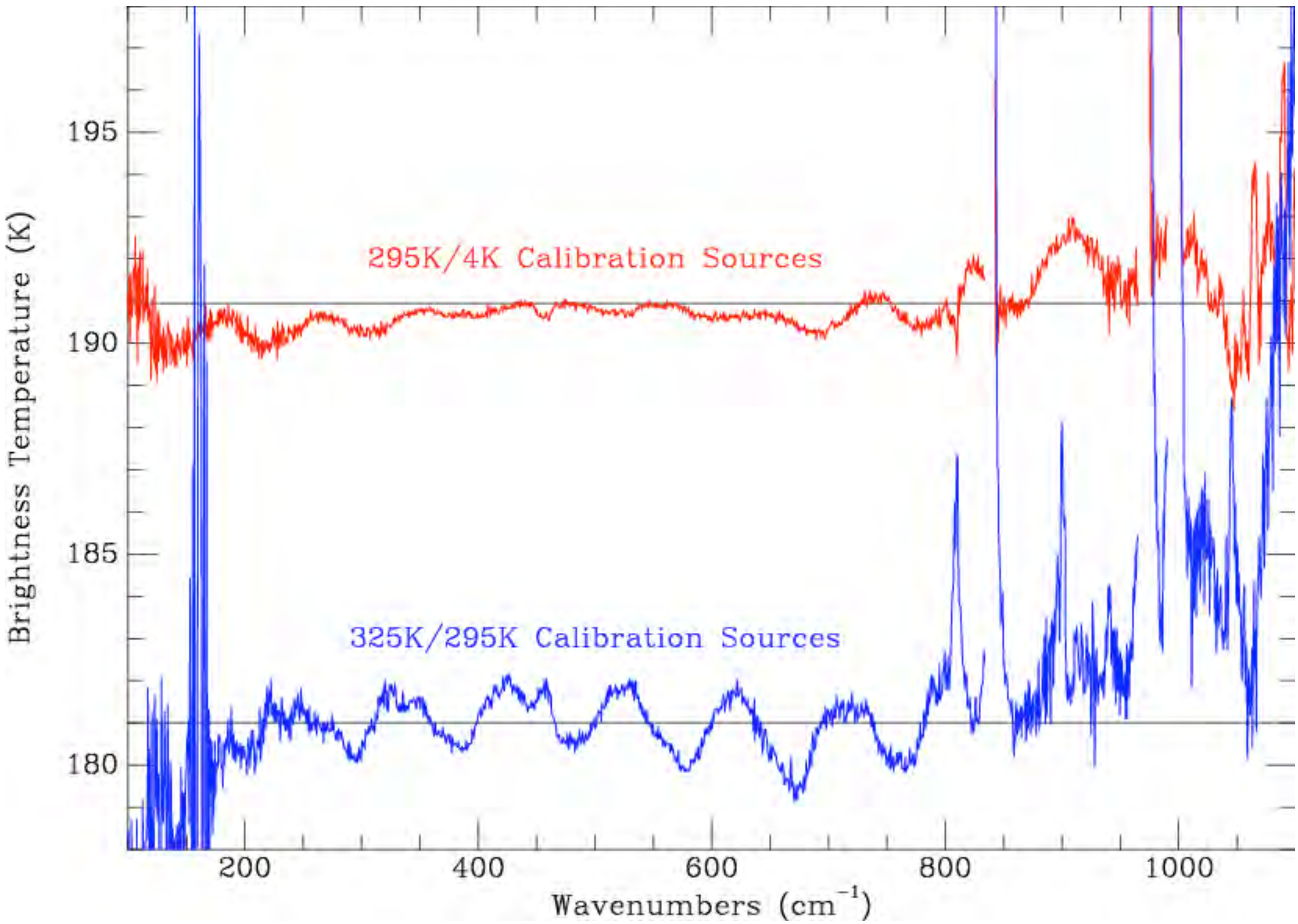
Uncorrected

Corrected

Radiance Calibration

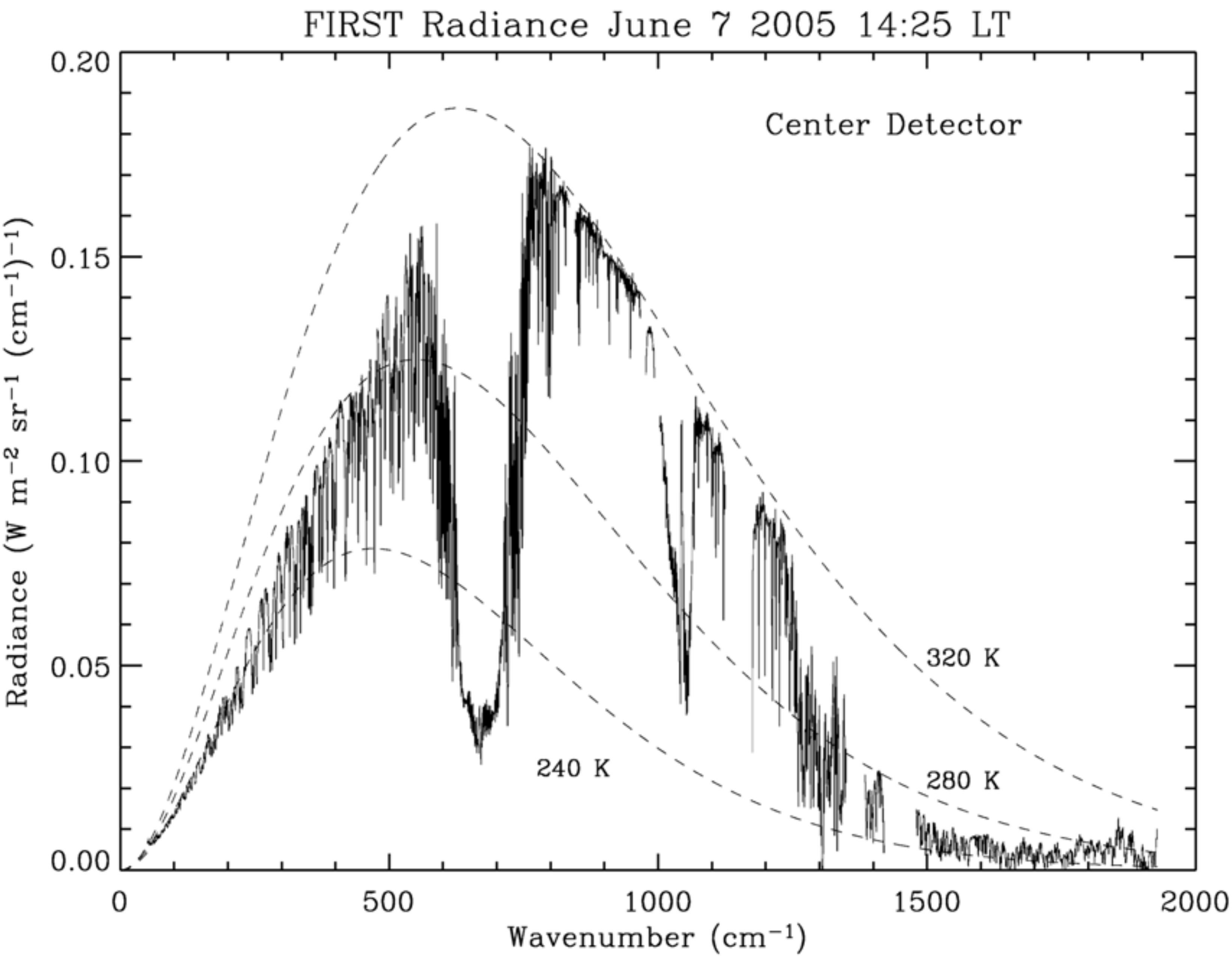
- Correct interferograms for small non-linearity using parameters derived from laboratory measurements.
- Assuming that spectrometer response is linear after correction, estimate responsivity and background for each detector using “warm” and “cold” sources.
- Different warm and cold sources for different configurations:
  - Laboratory: Ambient and helium-cooled blackbodies
  - Balloon: Ambient blackbody and cold space
  - Uplooking: Heated (~325 K) and ambient blackbodies

Laboratory Calibration Results: Worst Case Example



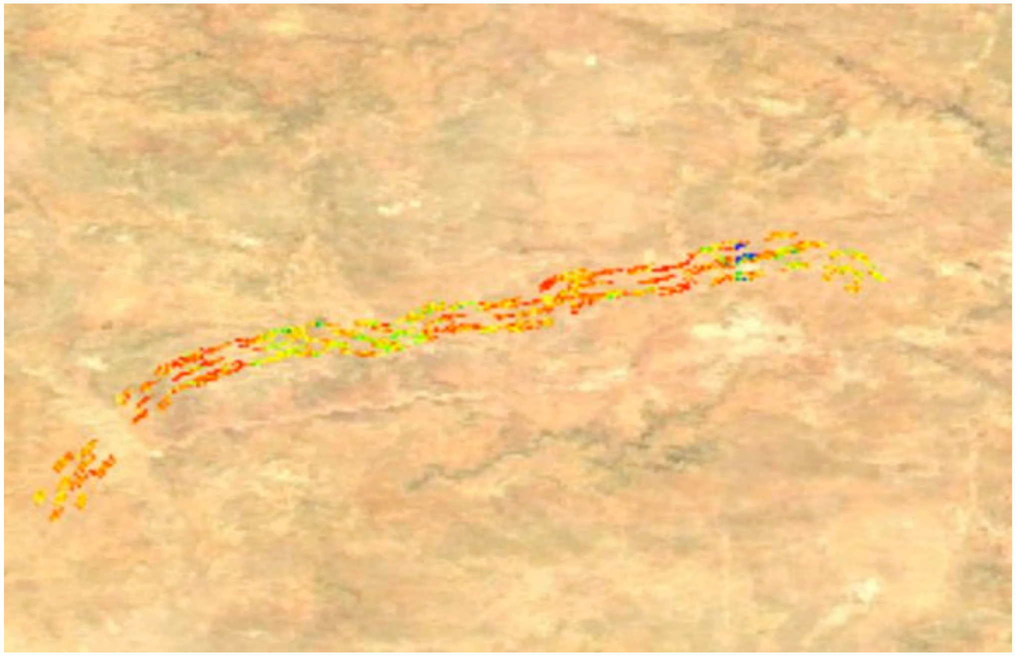
FIRST Ready for Launch

FIRST Thermal Infrared Spectrum

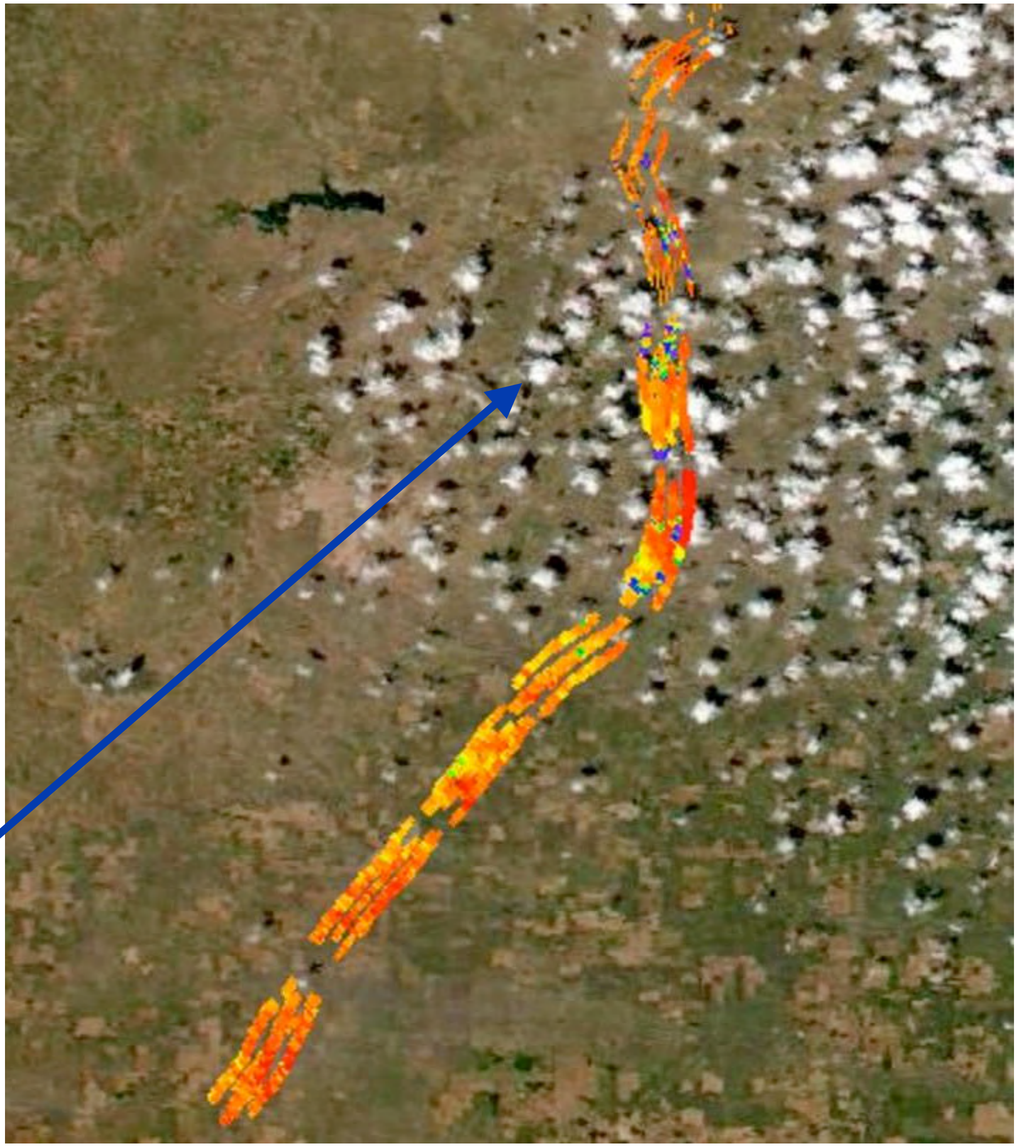


Mlynczak et al., GRL, 2006

FIRST 820 cm^{-1} Brightness Temperature 250 m MODIS Visible Imagery



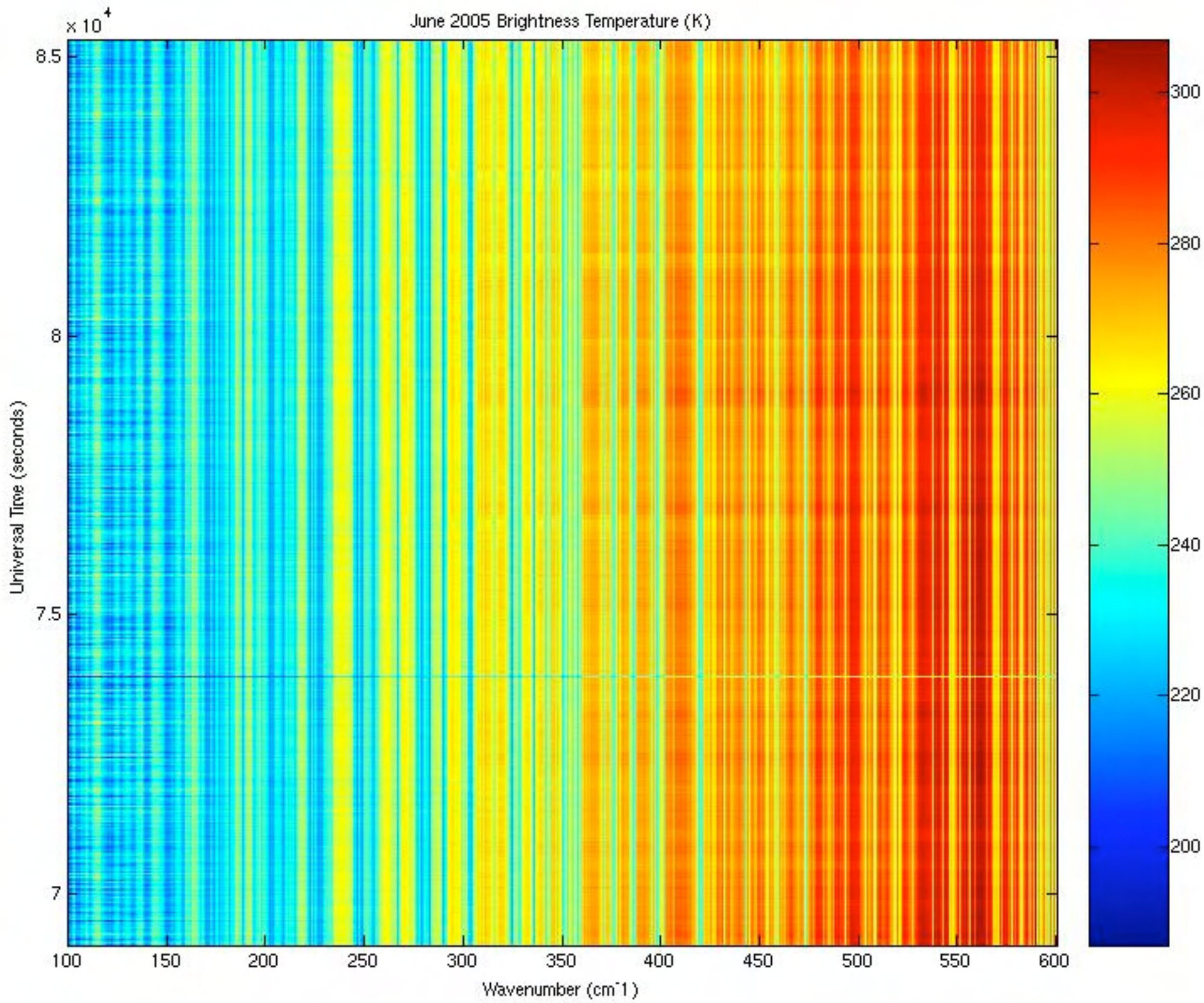
June 7, 2005



September 18, 2006;
Note clouds in image

FIRST Far-IR T_B June 2005 Flight

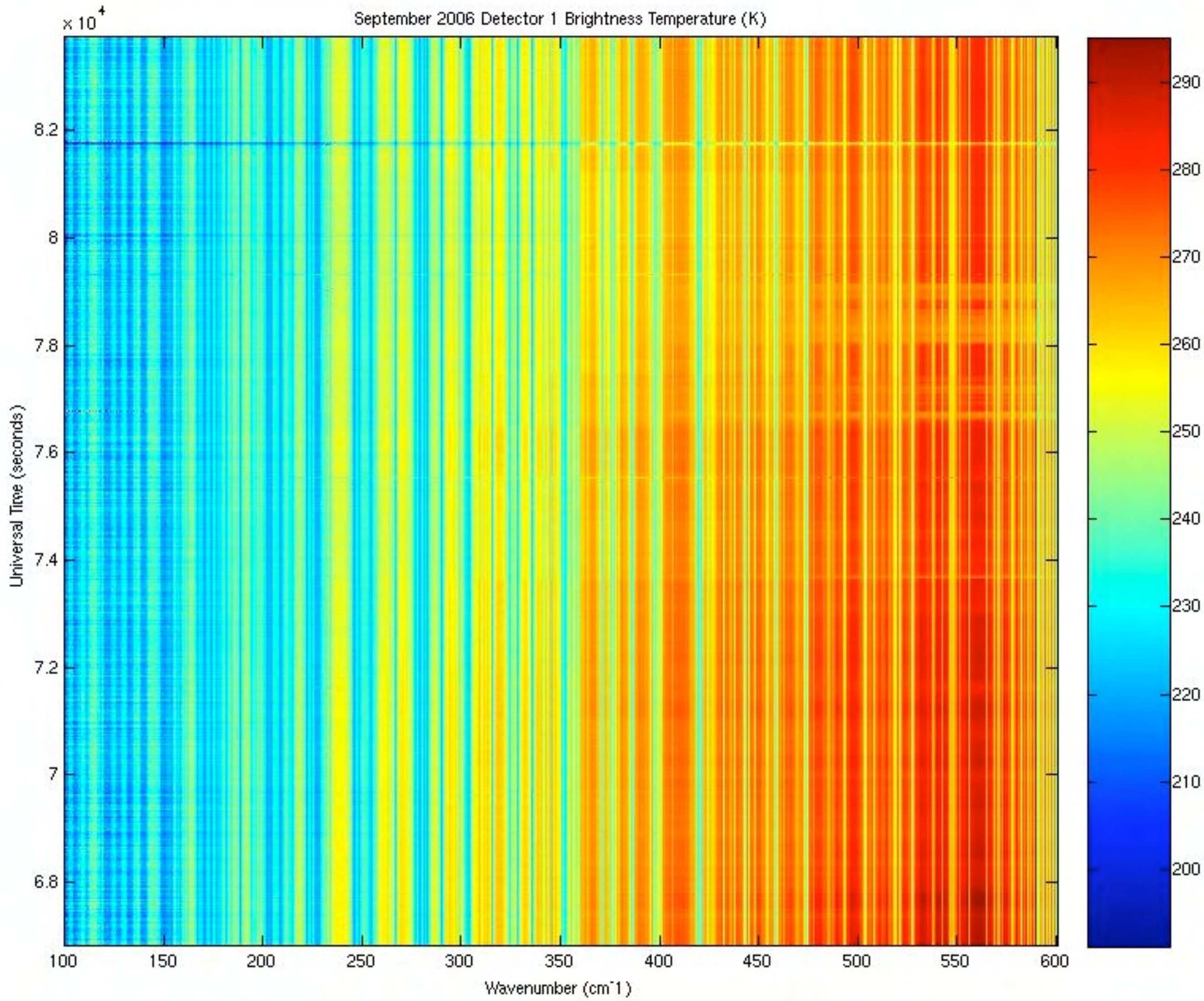
Time



Wavenumber

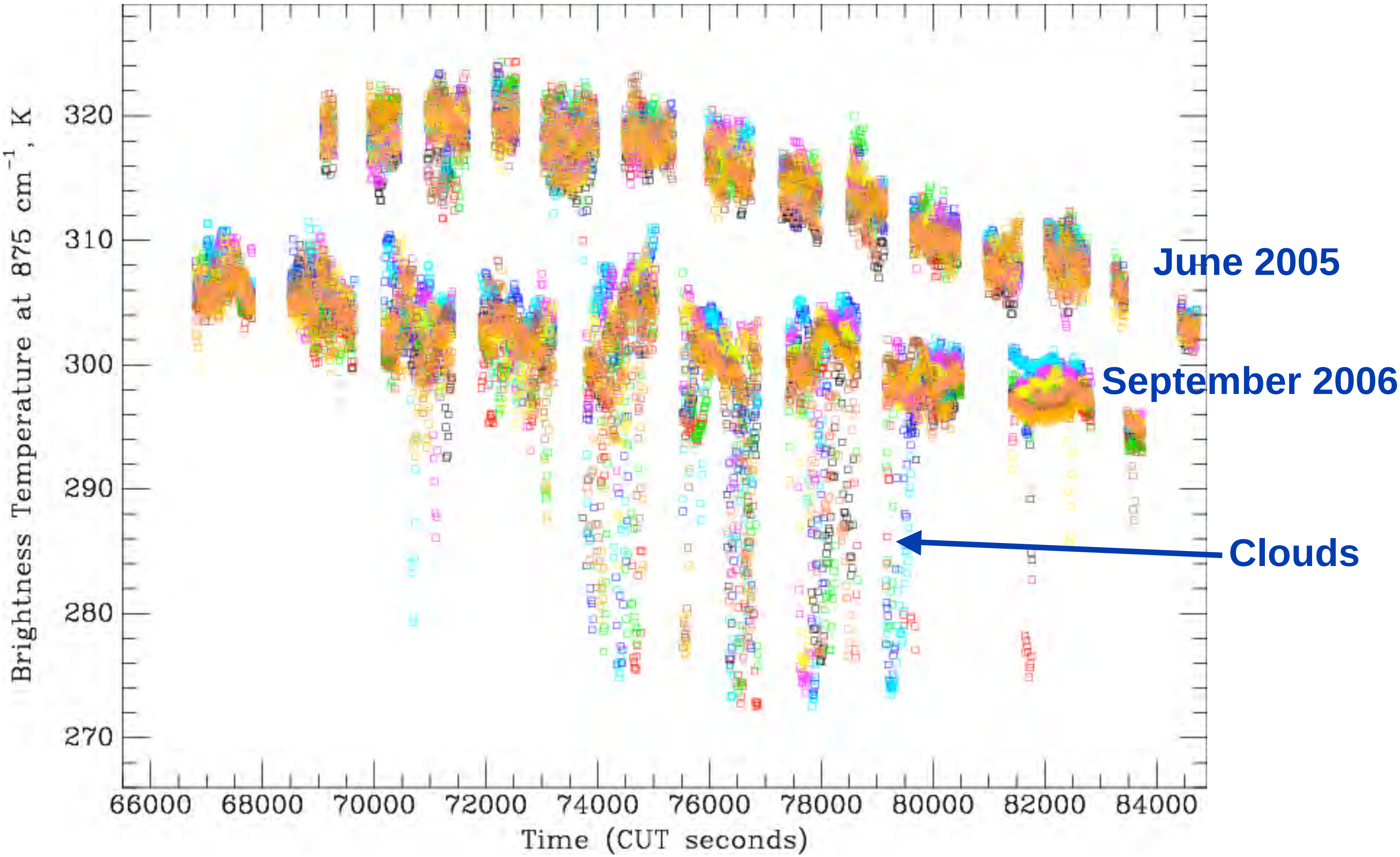
FIRST Far-IR T_B September 2006 Flight

Time

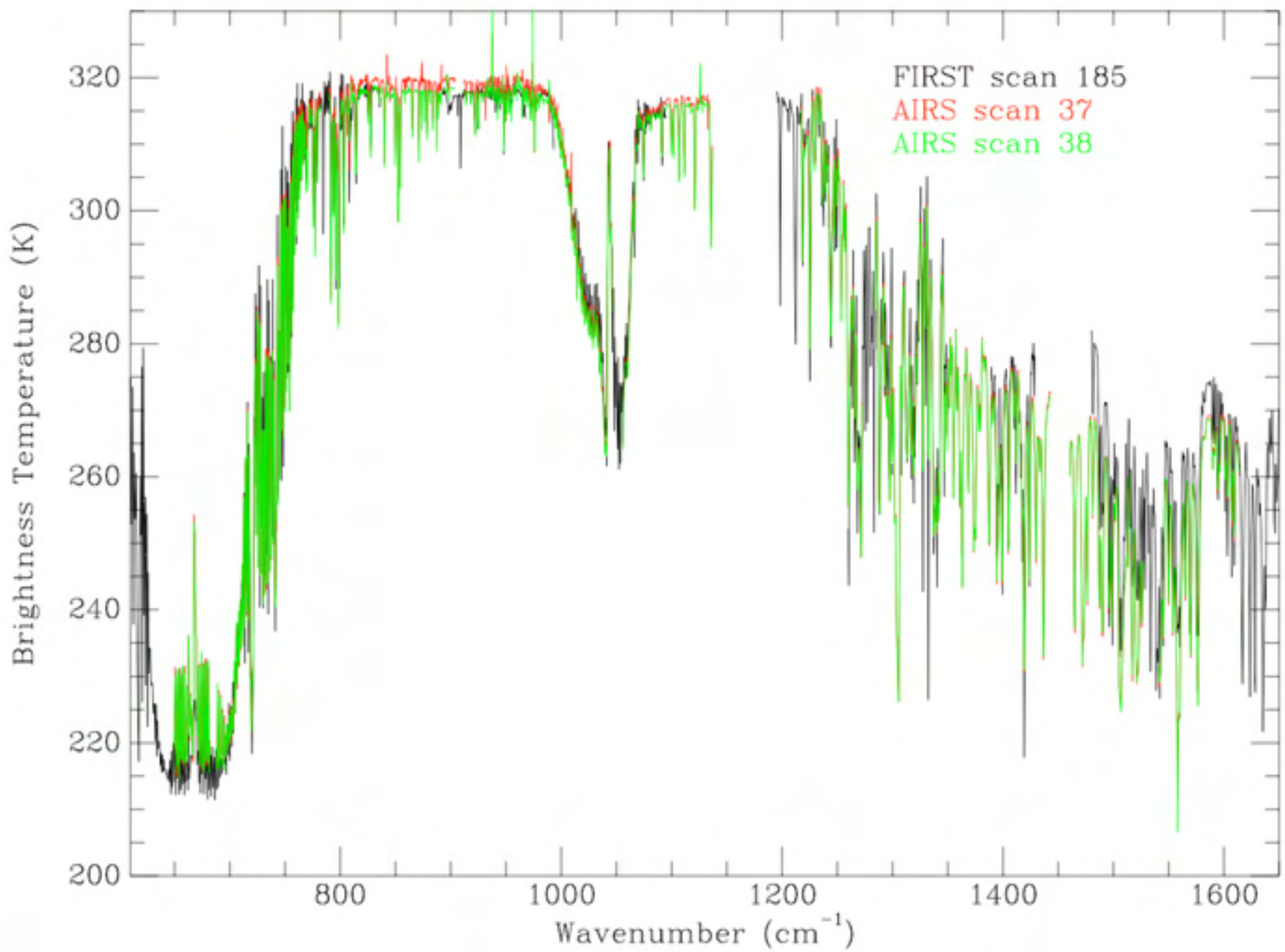


Wavenumber

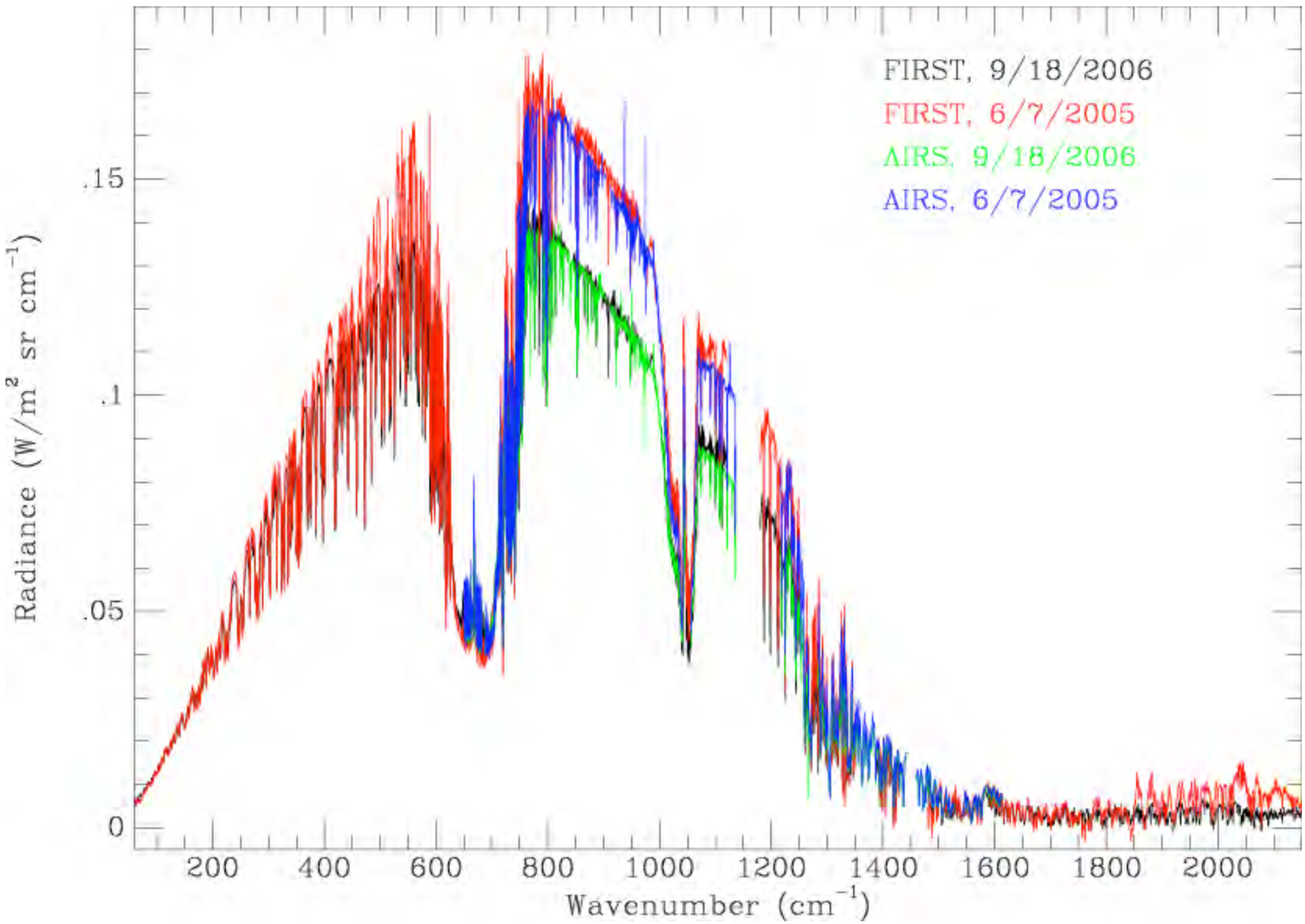
Brightness Temperature at 875 cm^{-1}



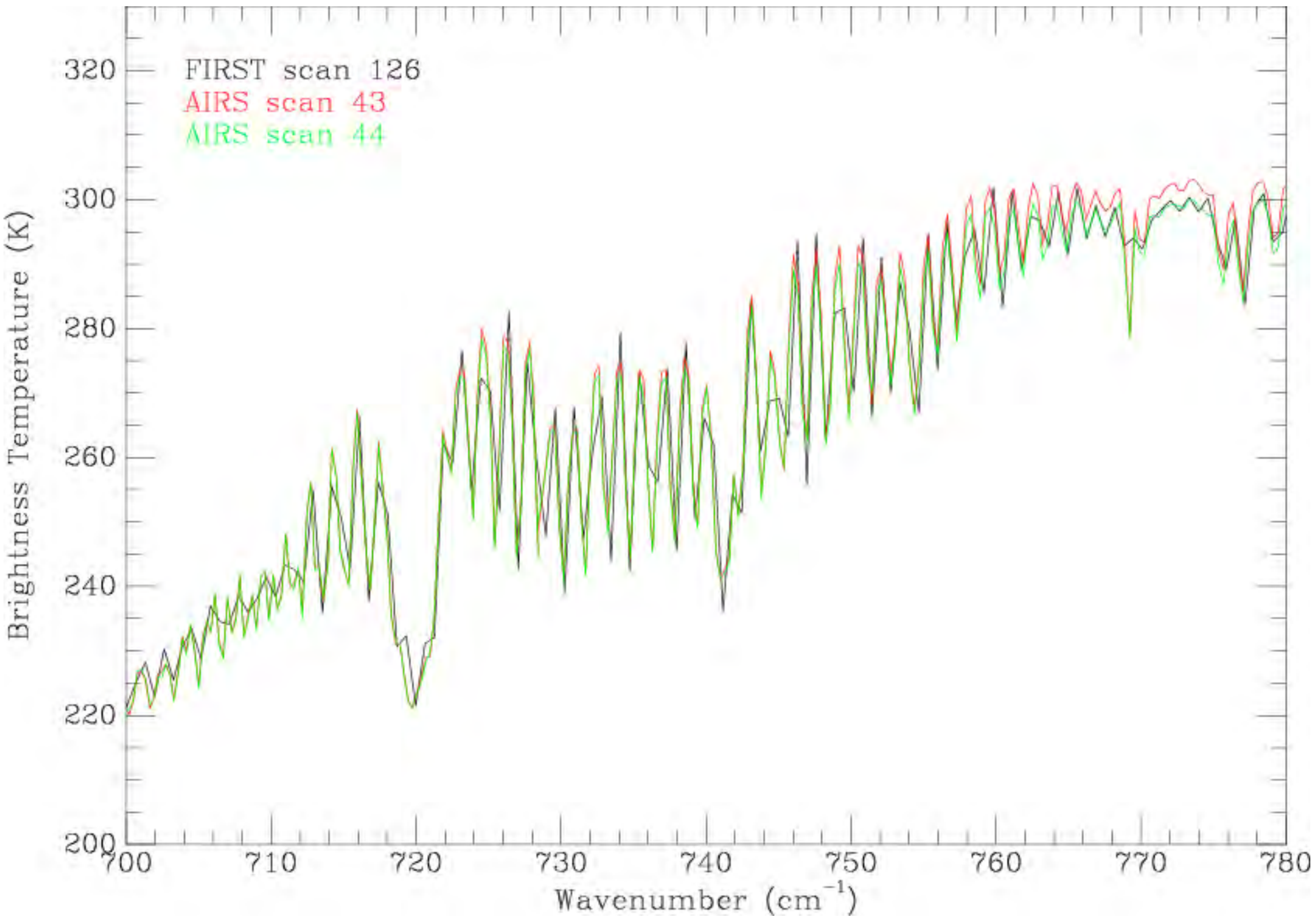
FIRST and AIRS T_B Comparison June 2005



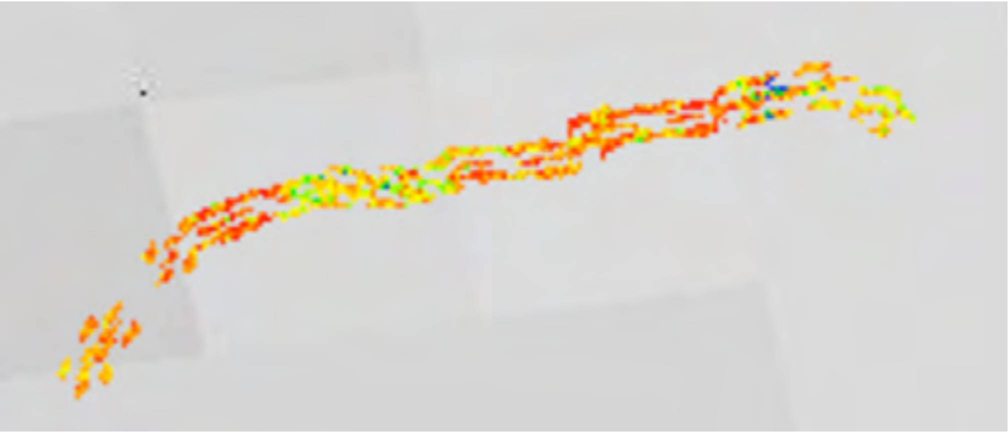
FIRST-AIRS Radiance comparison



Detailed AIRS Comparison



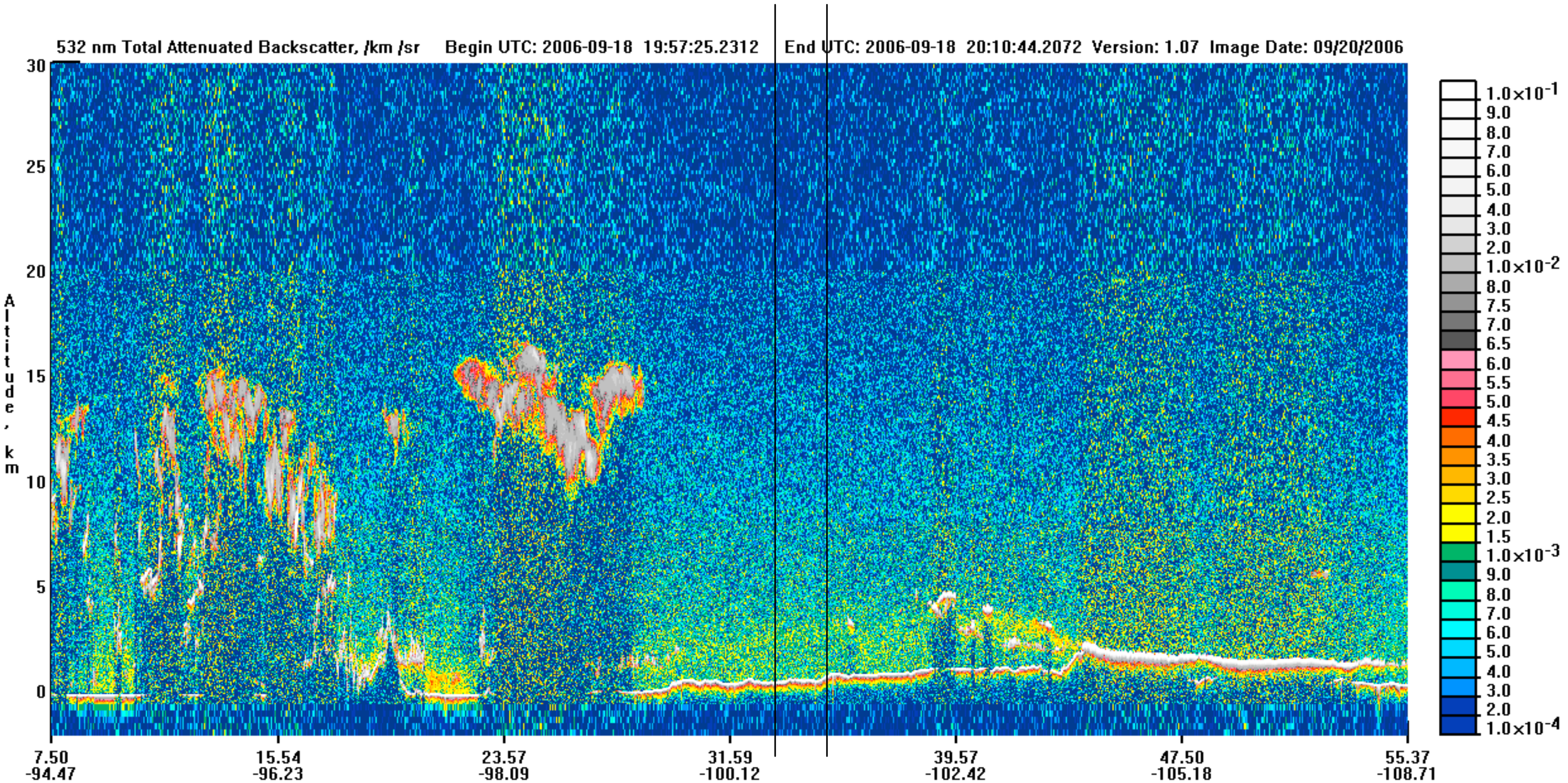
FIRST 820 cm^{-1} Brightness Temperature
AIRS 820 cm^{-1} Imagery



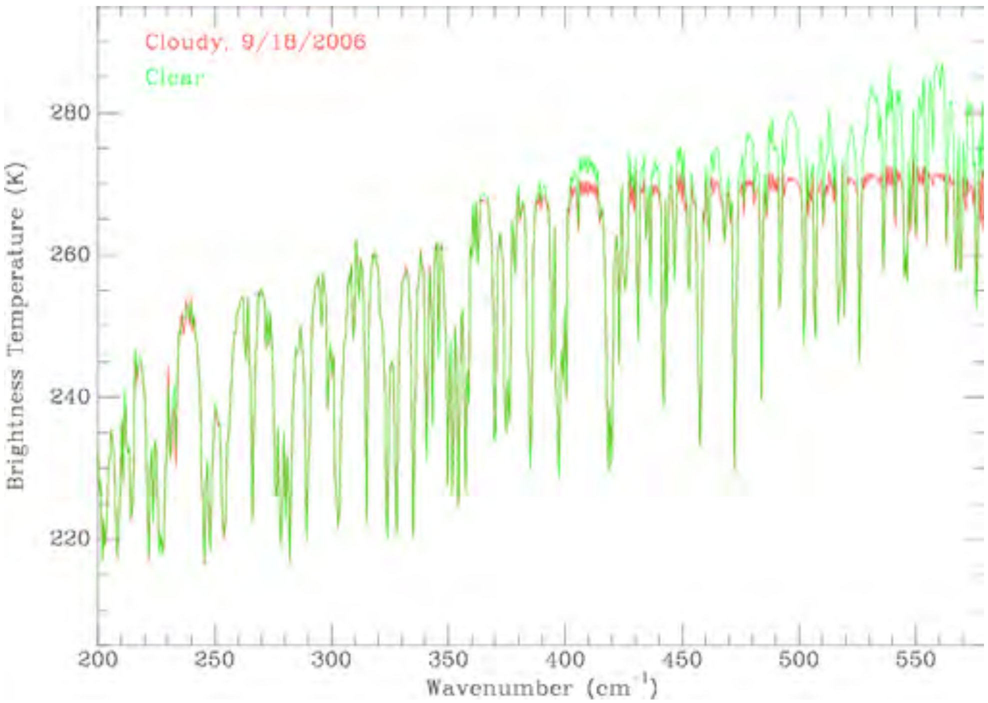
June 7, 2005

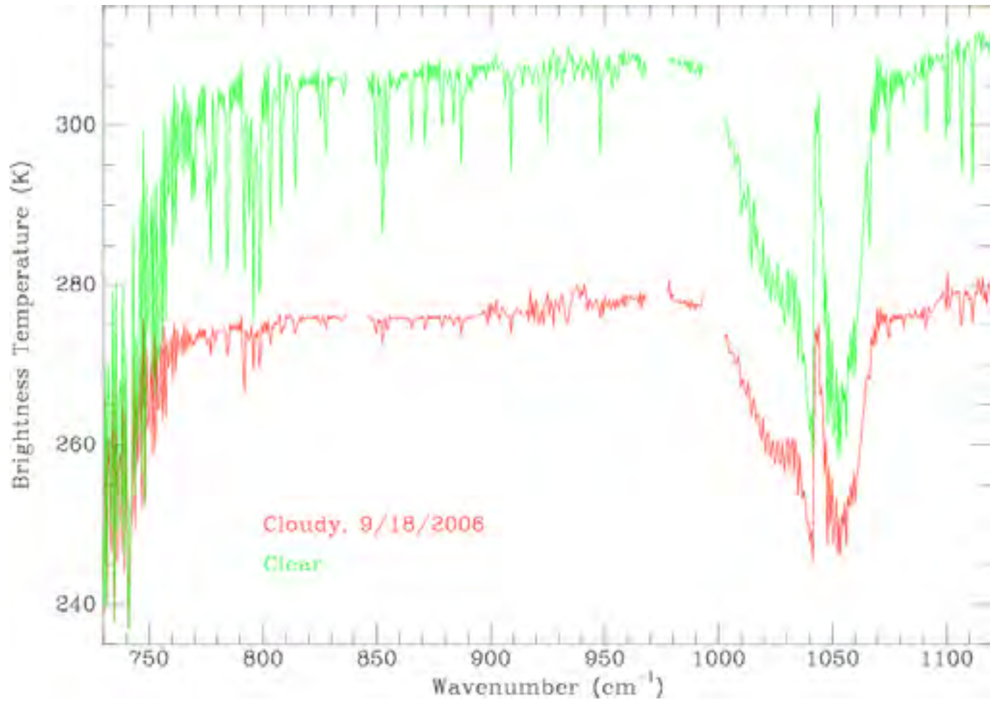
September 18, 2006

CALIPSO Data 9/18/2006



Comparison of Cloudy and Clear Spectra

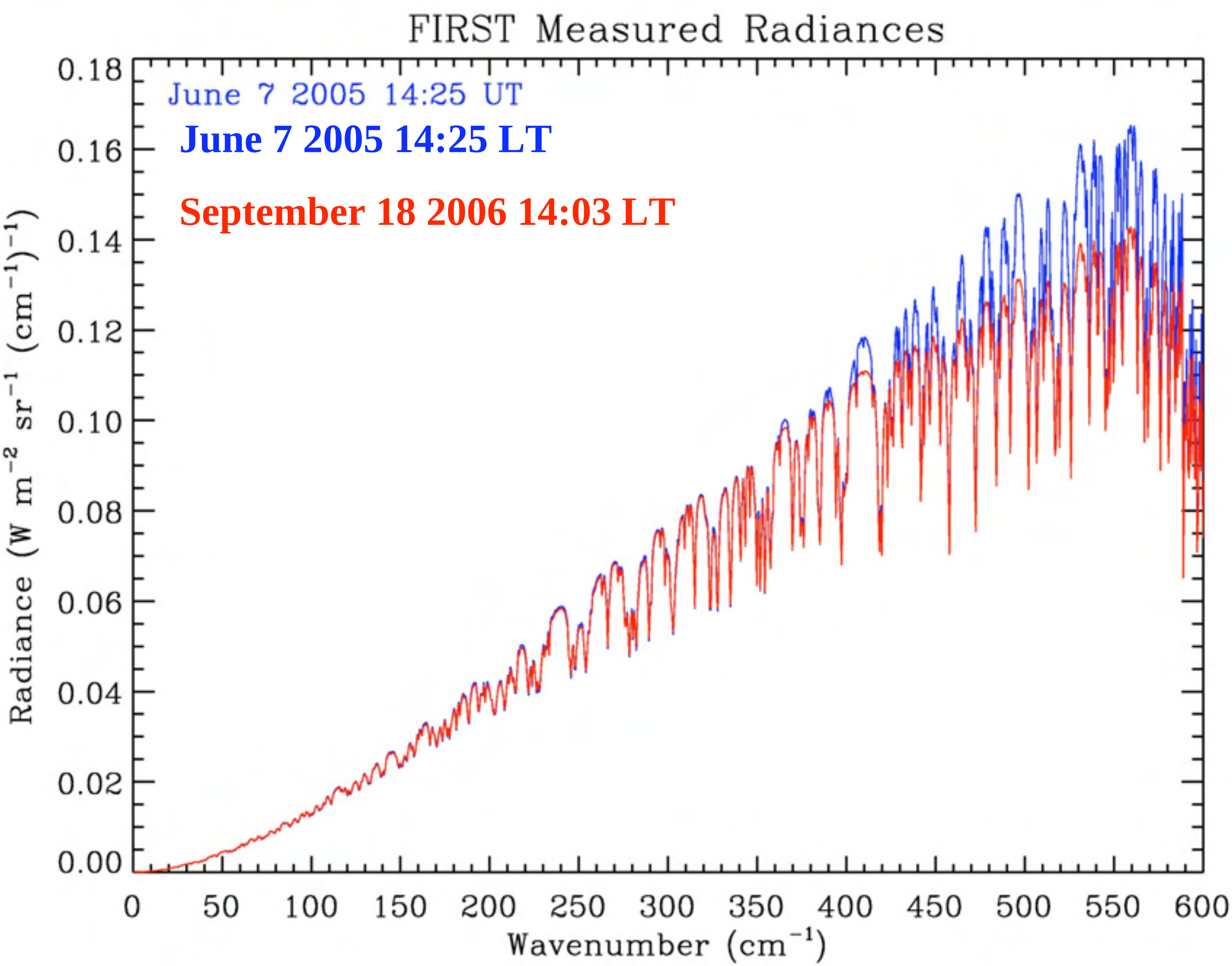




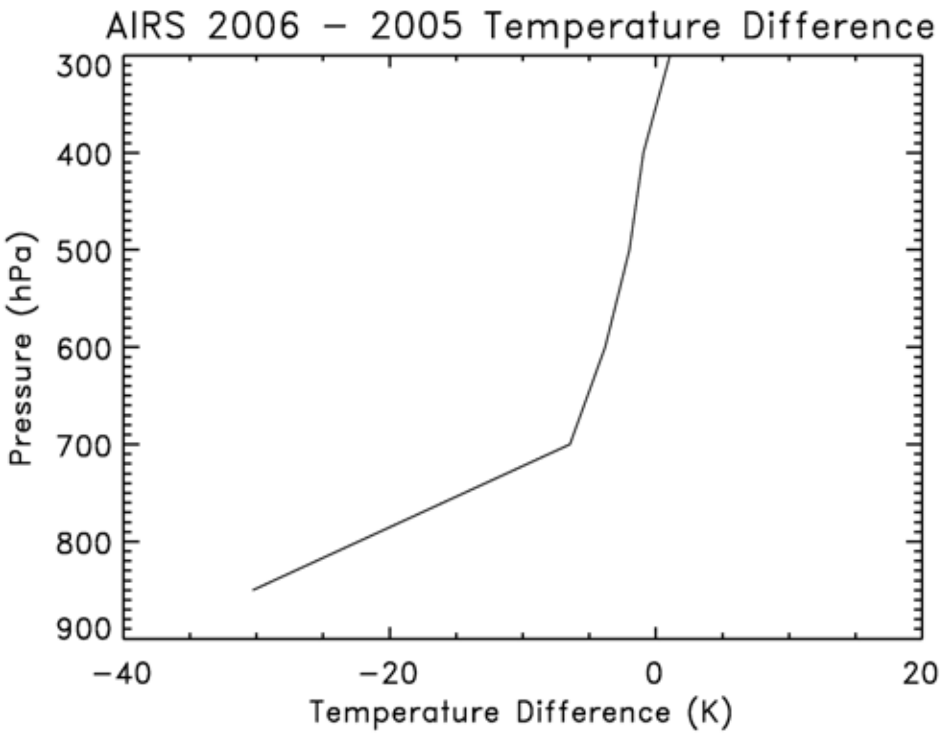
Far-Infrared

Mid-Infrared

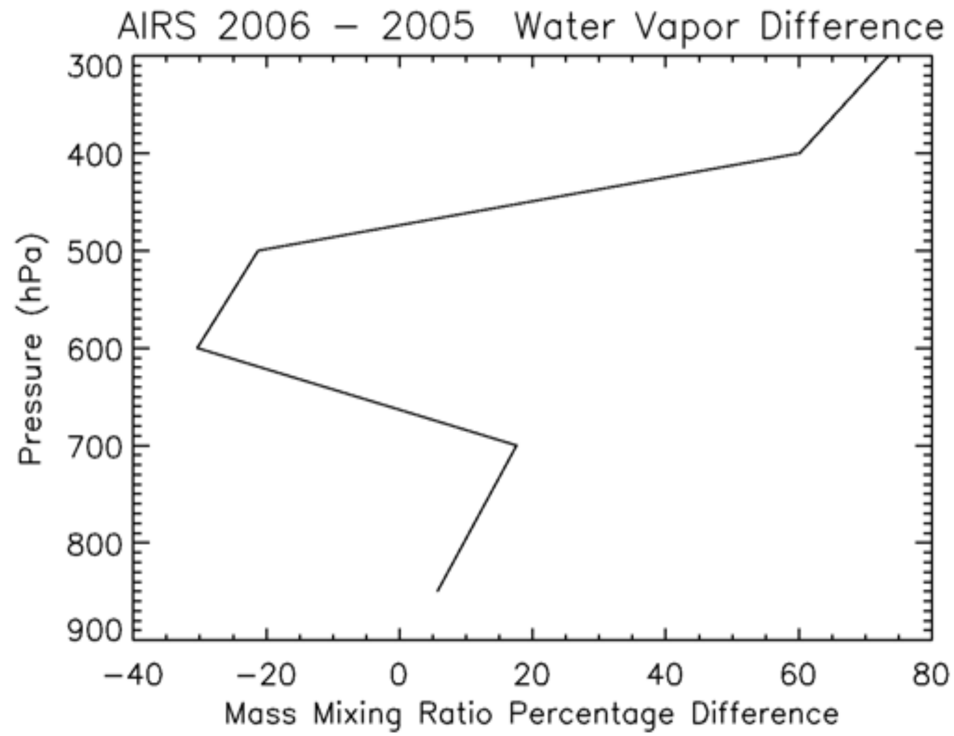
FIRST Radiances June 2005 and September 2006
- Clear Sky -



Far-IR Radiance Differences 2006 - 2005

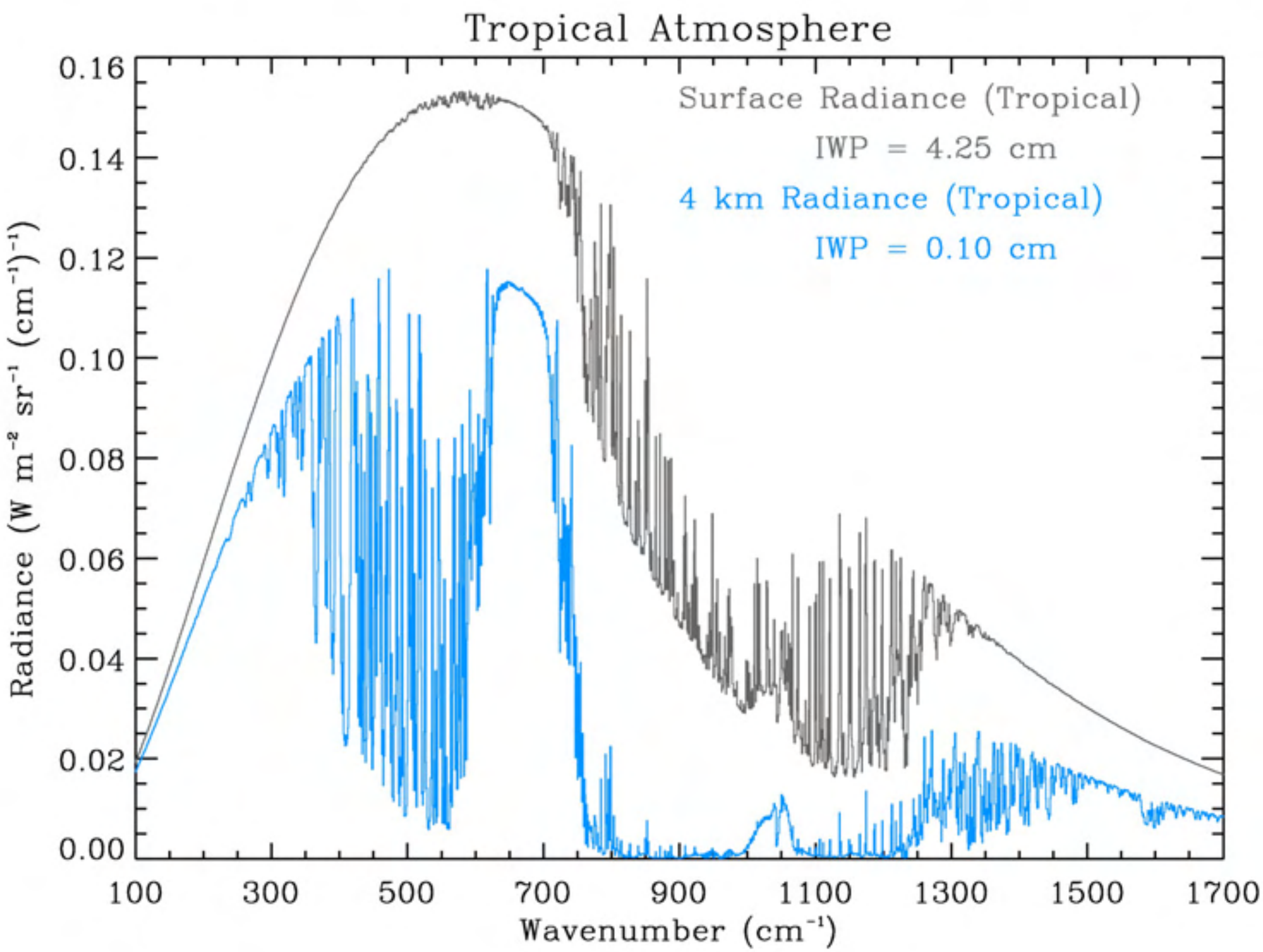


Lower troposphere much cooler

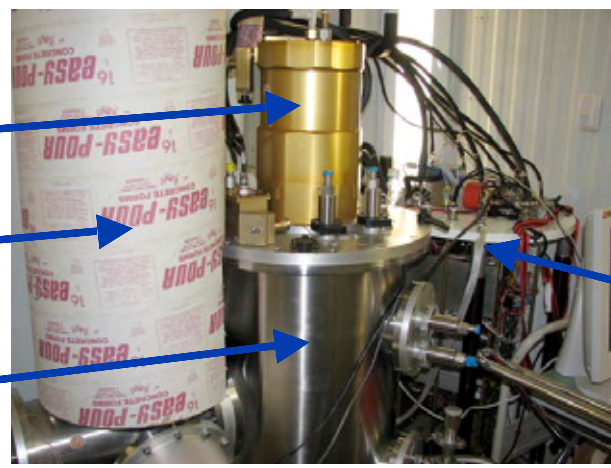


Mid-troposphere much drier

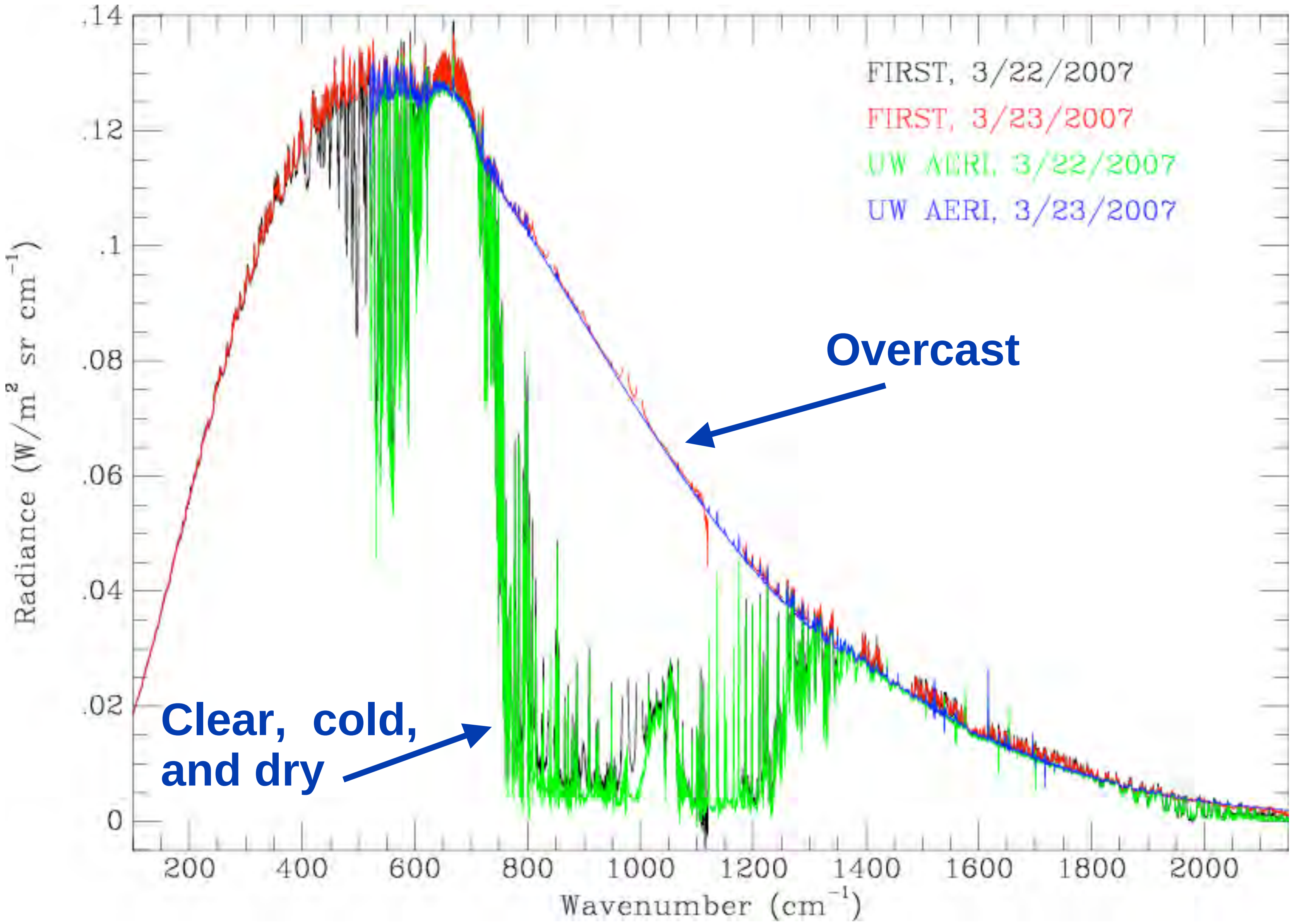
Example: Ground-Based, 4 km Zenith Views Mauna Loa, HI



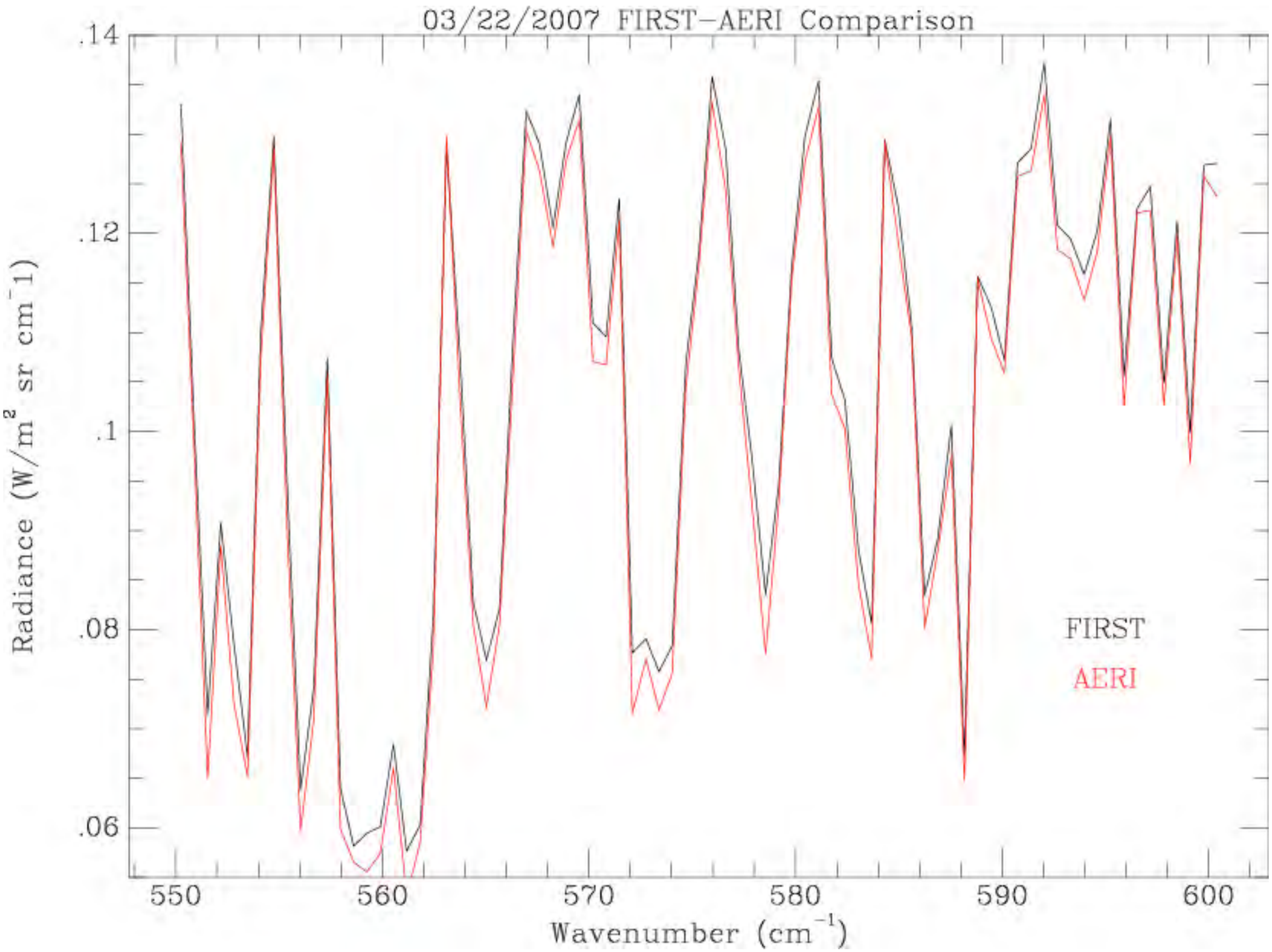
FIRST at University of Wisconsin March 2007



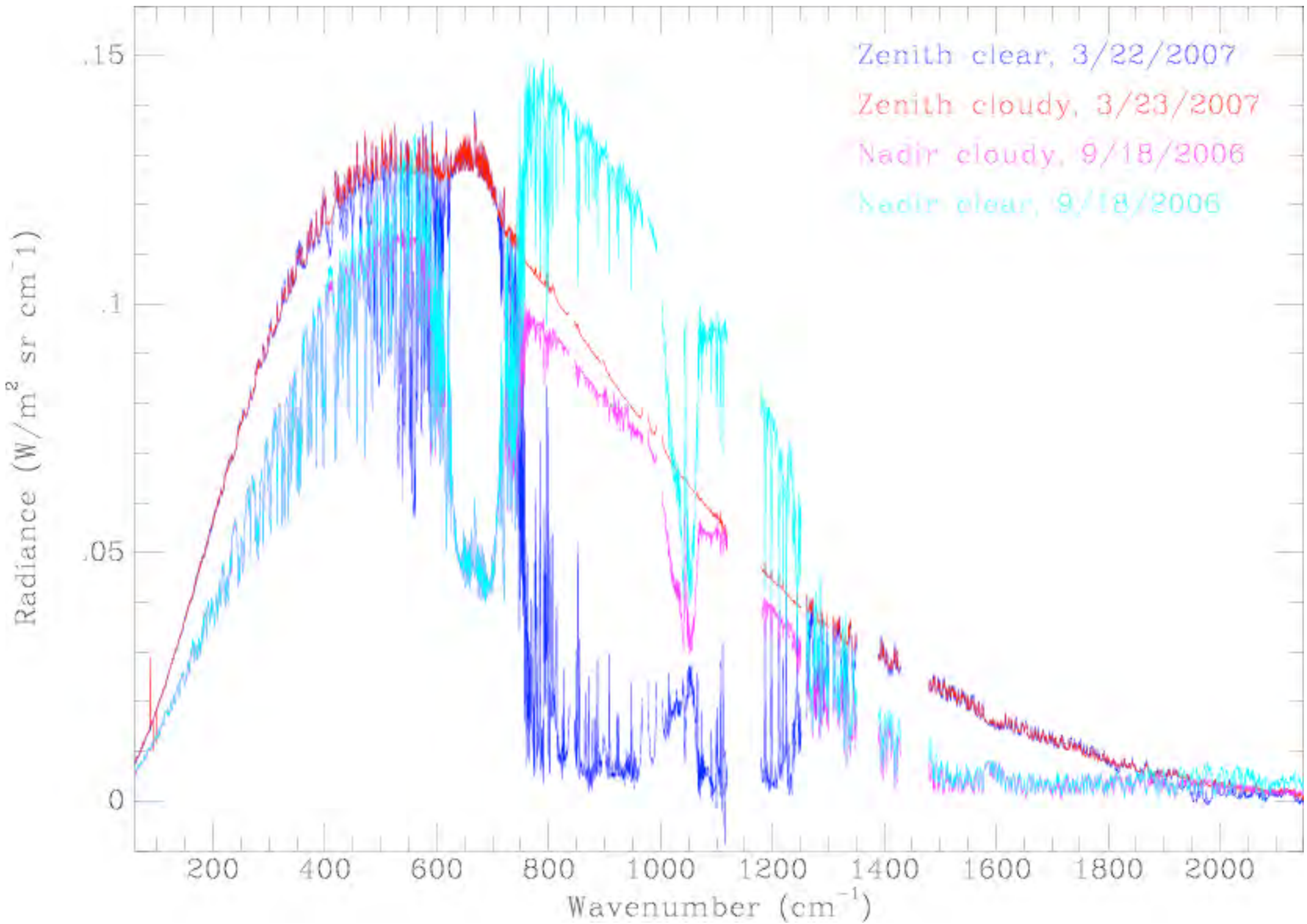
AERI-FIRST Comparison



AERI-FIRST Detail



Compare Balloon and Ground Spectra



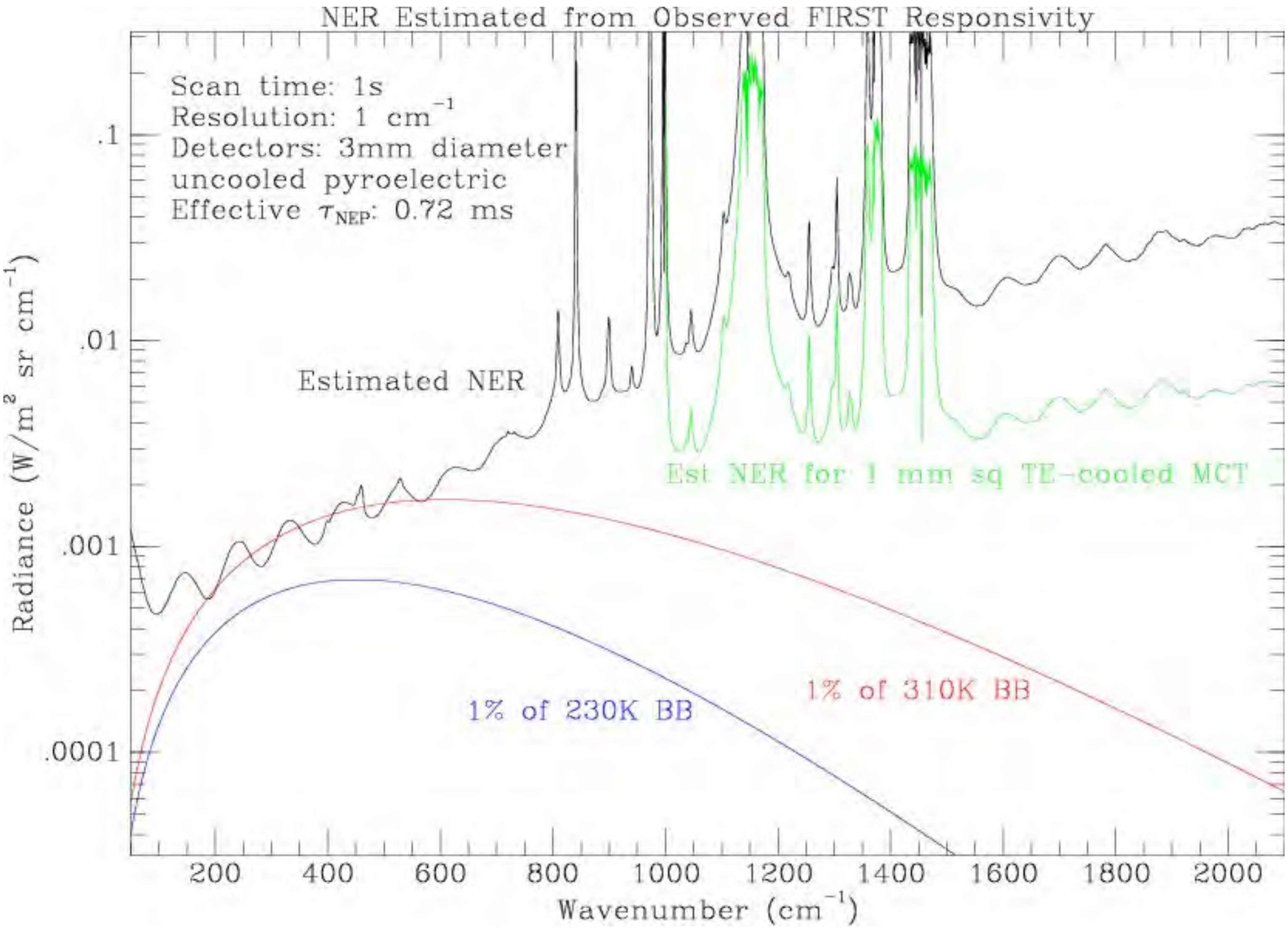
FIRST Summary

- FIRST completed on schedule and within IIP budget
- Average systematic errors less than 0.001 W/m^2 sr cm^{-1} from 150 to 800 cm^{-1}.
- Nearly complete spectral coverage of outgoing longwave radiation
  - Beamsplitter and window absorption result in some small gaps in coverage
- Data available as HDF5 files - 15 groups worldwide
  - Ask and you shall receive!
- Comparison with space and ground standards (AIRS, AERI) is excellent
- Data, instrument analysis is ongoing.

On to CLARREO

- FIRST designed to demonstrate technology for “wall to wall” high spatial resolution global coverage, hence an imaging plane-mirror FTS
- Apparent CLARREO requirements are substantially less stringent in coverage:
  - One detector vs. 100
  - CLARREO FOV 100 x larger
- Simpler, smaller, FTS to achieve CLARREO goals especially in Far-IR
- All knowledge and technology developed in FIRST applicable to CLARREO (beamsplitters; calibration; etc.)
- Preliminary study shows uncooled FIRST NER ~1% of 250 K blackbody over 100 to 600 cm^{-1}.
- Looking to derive “hard” measurement requirements from this workshop to complete design of FIRST/CLARREO

Initial NER Estimate of Warm FIRST Sensor



FIRST - Concluding Summary

- Far-IR fundamental to Earth's Climate
  - Harries et al., *The Far-Infrared Earth*, Rev. Geophys., 2007
- FIRST has demonstrated technology to make routine far-IR measurements from space - essentially entire thermal IR
  - Integrated sensor at TRL-6
- FIRST nominal performance:
  - Systematic Errors: ~0.7 K @ 600 cm^{-1}
  - Precision: 0.1 K rms
- Improvements to this performance anticipated in CLARREO-specific design:
  - Optics (field stops, etc.); electronics; scan mechanism; metrology; 4 port FTS vs. 2 port; improved blackbodies…..

Almost home...

Partners

We gratefully acknowledge our partners:

- Spectrometer and flight electronics designed and built by Space Dynamics Laboratory, Utah State University
  - Gail Bingham, Stan Wellard, Harri Latvakosky, Mike Watson, Jason Swasey, Angie Minichello, Dave Morse, Dave Anderson, and others.
- Beamsplitter and technical support provided by Smithsonian Astrophysical Observatory
  - Wes Traub and Ken Jucks.
- Project funded by Instrument Incubator Program, Earth and Space Science Technology Office, NASA Headquarters.

Partners (continued)

We gratefully acknowledge our partners:

- NASA SMD
  - Don Anderson, Ken Anderson, Janice Buckner, Mike Kurylo, George Komar, Jack Kaye, Hal Maring
- NASA Balloon Program Office
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  - Bill Stepp and team
- Jet Propulsion Laboratory
  - Jess Landeros and Jim Margitan
- AERI Team @ U. Wisconsin
  - Dave Tobin, Dave Turner, Fred Best, Hank Revercomb

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Formal Publications

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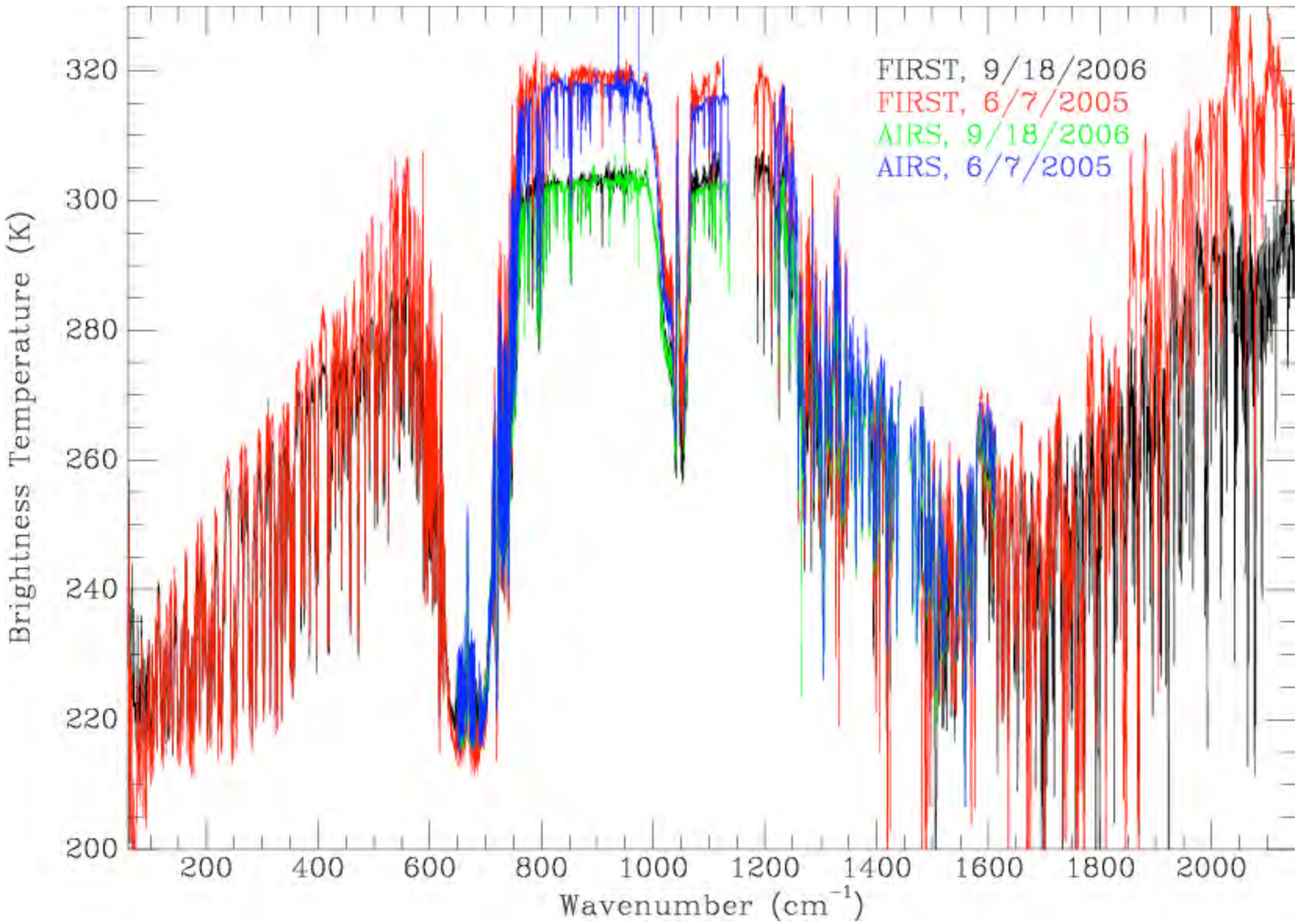
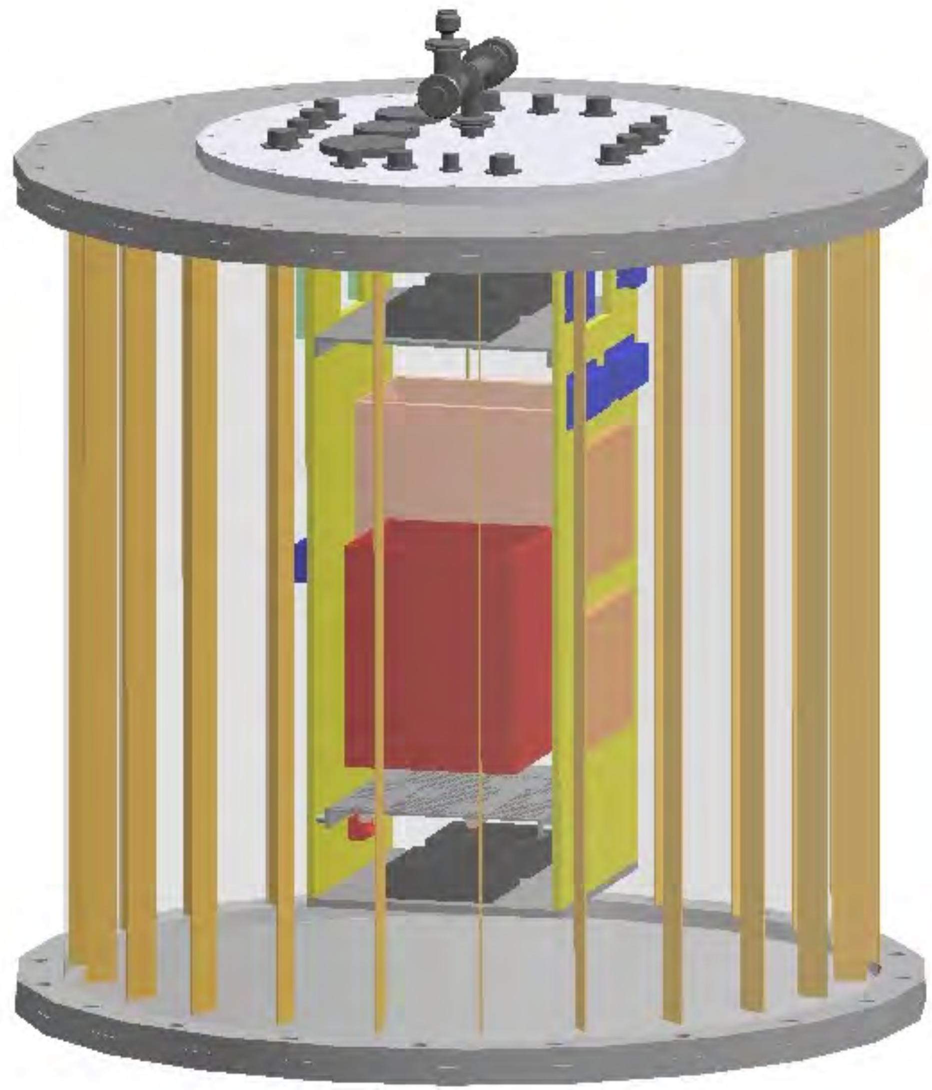
Backup Slides

FIRST-AIRS Temperature comparison

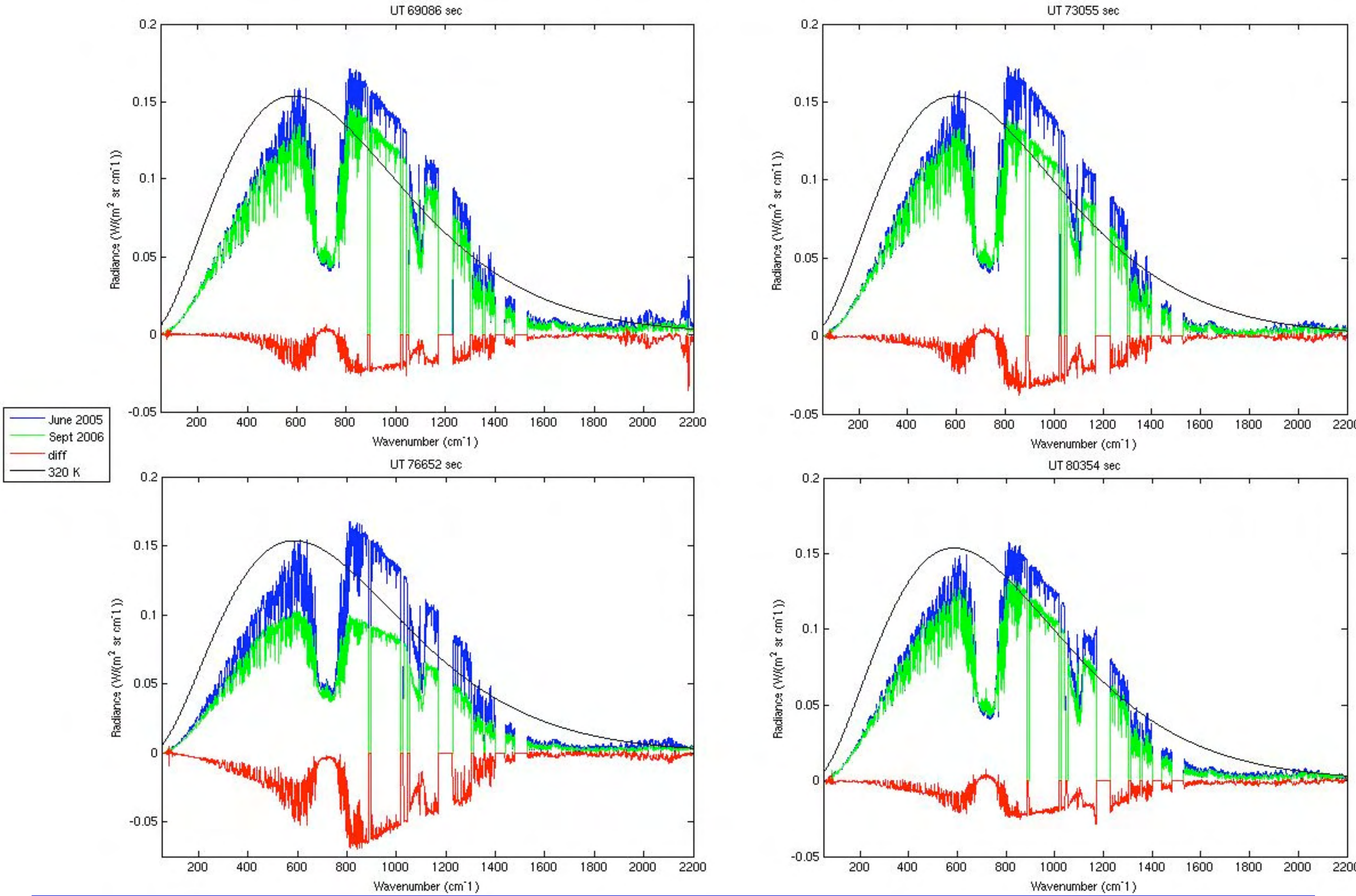


Flight Electronics Overview

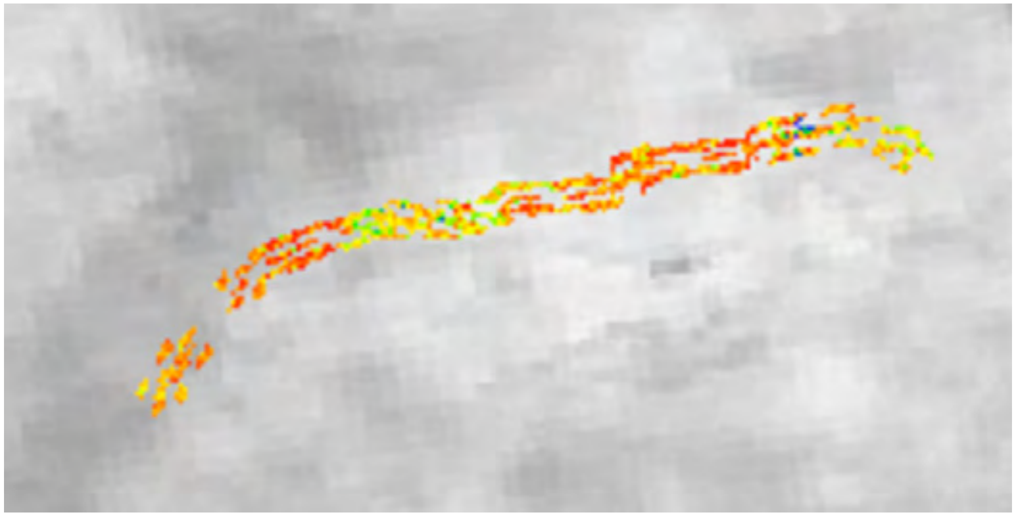
- Enclosure constrained by need to dissipate ~275 W of heat generated by COTS computer and signal conditioning electronics.
- Designed to maintain proper temperature and pressure at balloon altitude.



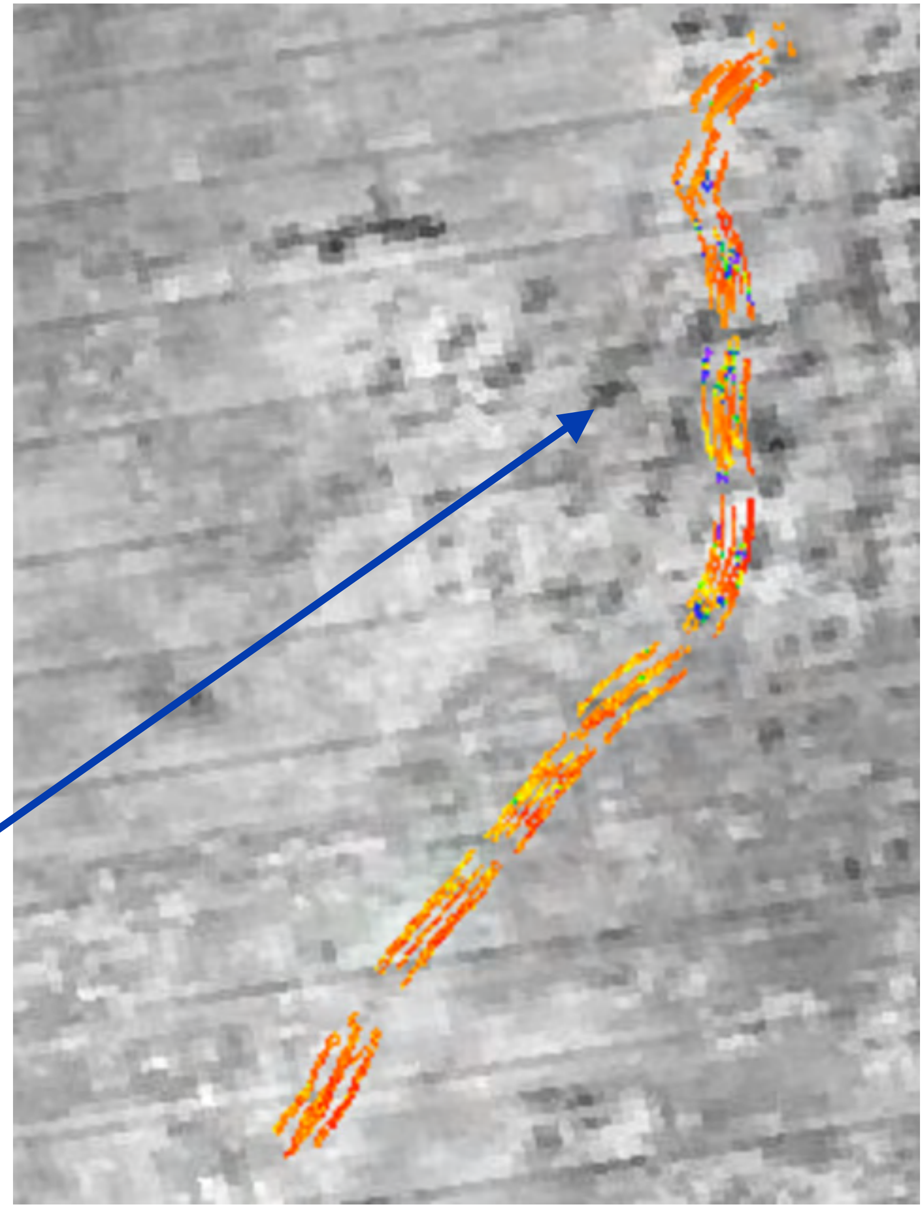
Radiances and Differences
June 2005 and September 2006



FIRST 820 cm^{-1} Brightness Temperature 1 km MODIS IR (Channel 32) Imagery

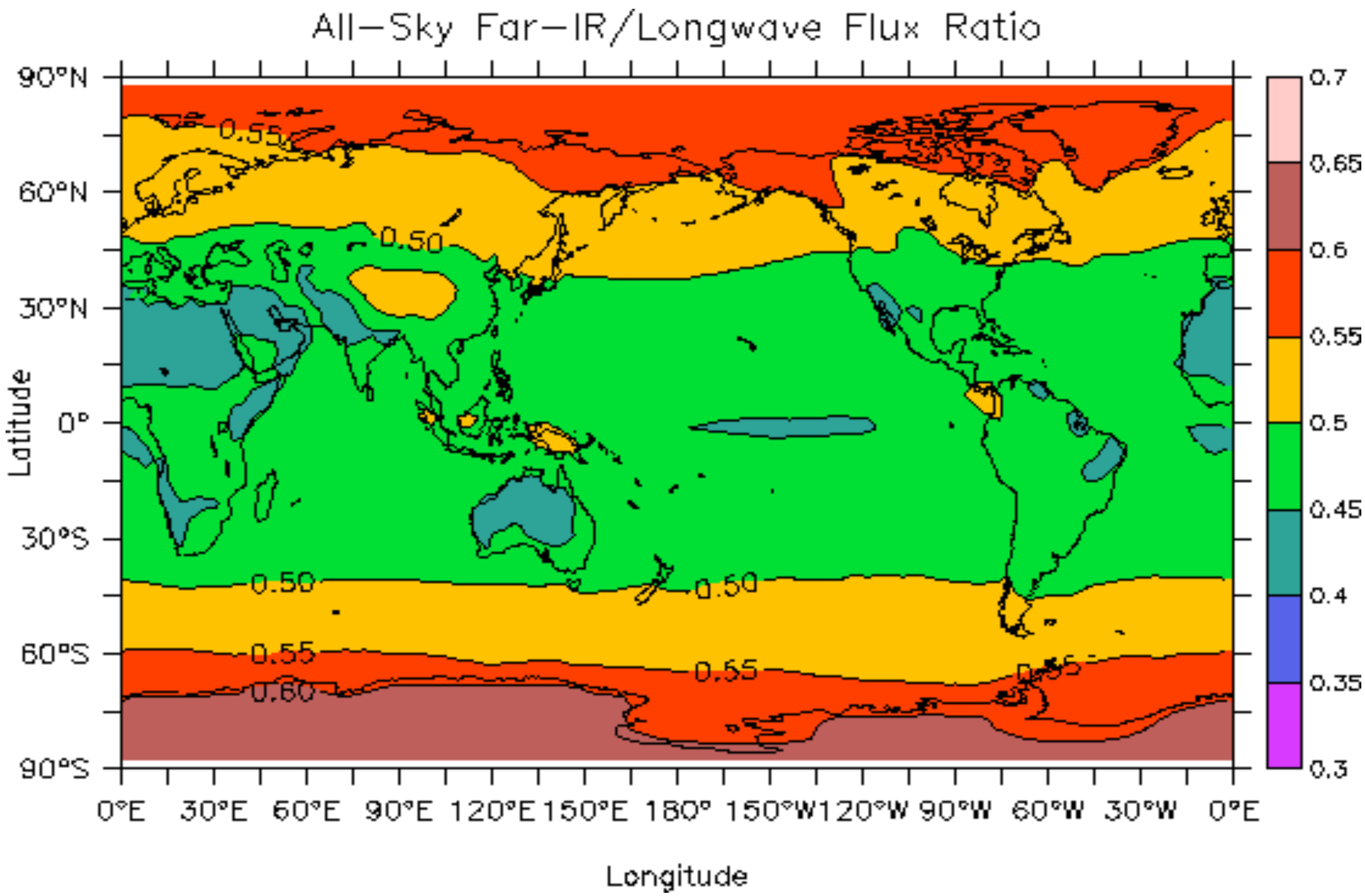


June 7, 2005



September 18, 2006; Note clouds in image

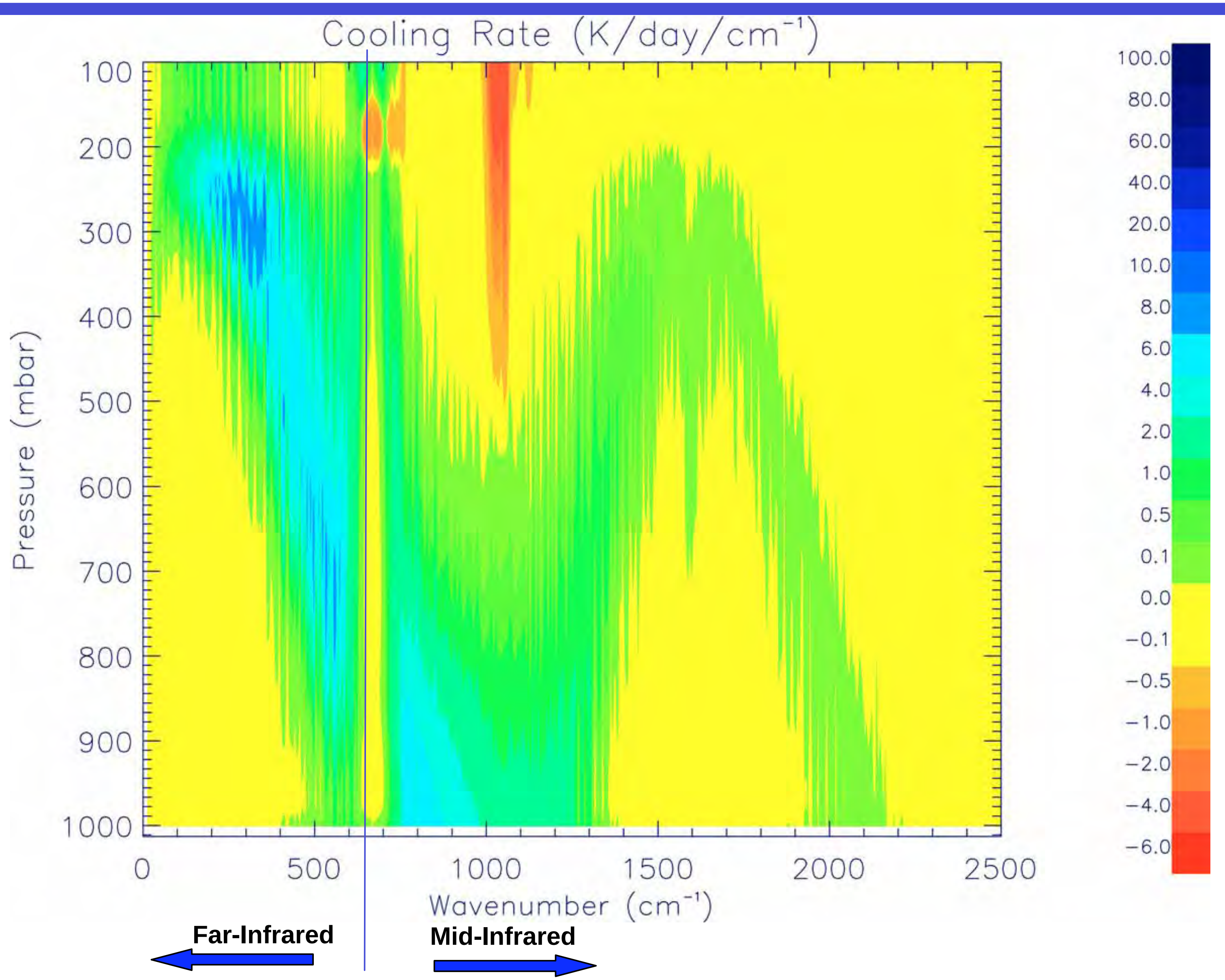
Fraction of OLR in Far-IR



Annual mean TOA fluxes for all sky conditions from the NCAR CAM

Reference: Collins and Mlynczak, Fall AGU, 2001

Infrared Cooling Rate (mK/day/cm^{-1})



Brightness Temperature at 279 cm^{-1}